New HBT-EP wall and control coil system design and future experimental plans

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Princeton Plasma Physics Laboratory

Talk outline

• Motivation and experimental goal of new wall, control and sensor coil arrays on HBT-EP

• Examples of kink nonrigid, multimode plasma response to external magnetic perturbations

• Plans for investigating these issues on HBT-EP

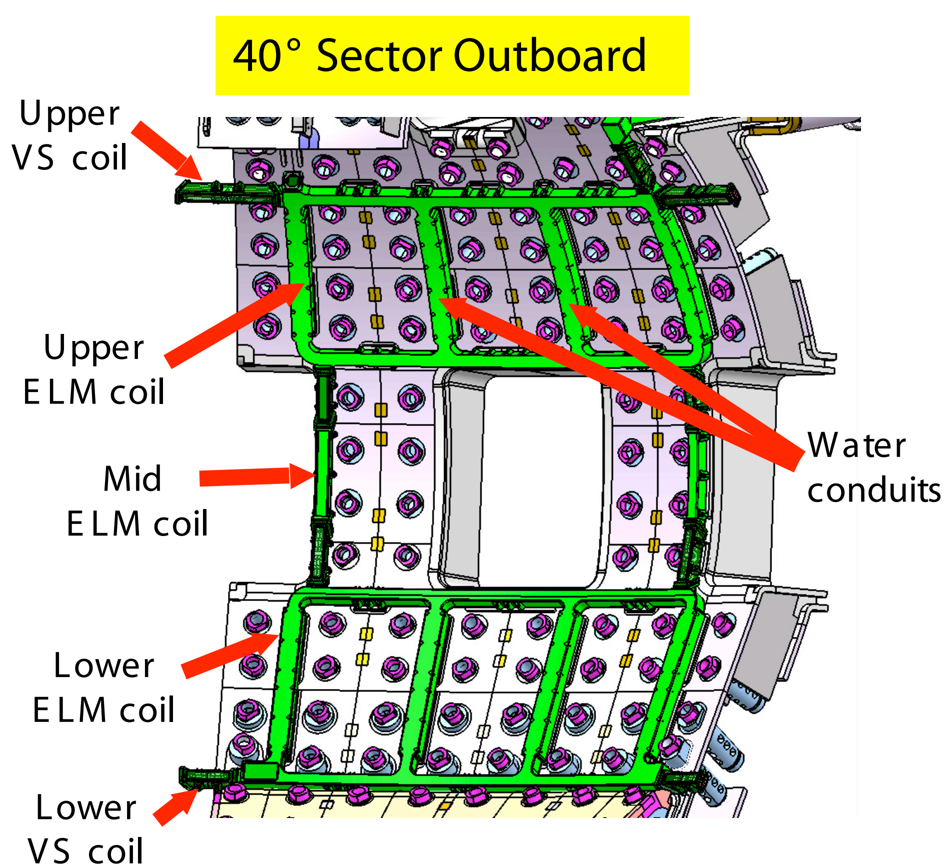
Physics motivation: Understand nonrigid, multimode plasma response to magnetic perturbations

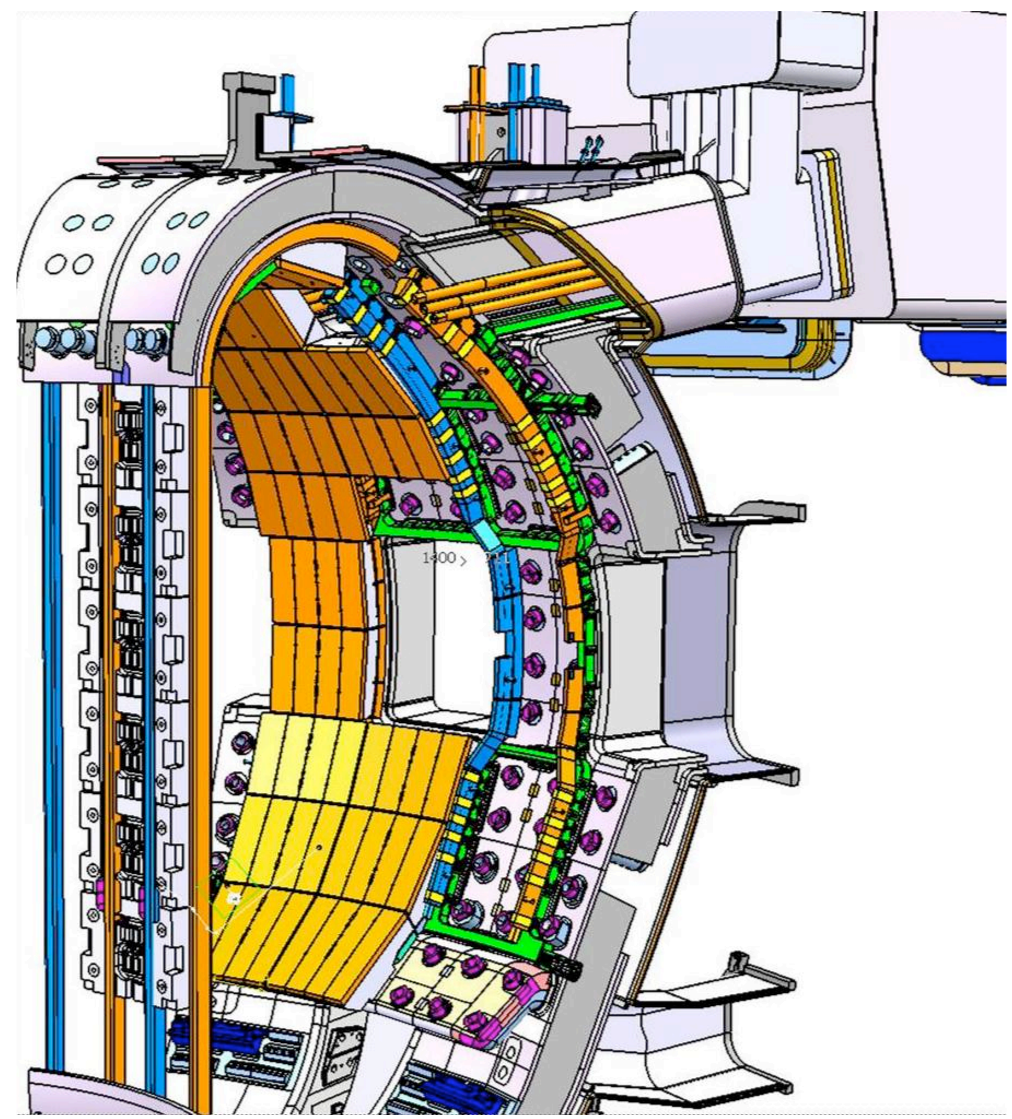
- Important in predicting and optimizing performance of
  - ELM mitigation
  - Error field correction
  - Kink feedback systems

- Experimental goal: Measure edge magnetic perturbations and plasma response with unprecedented detail and accuracy in a tokamak

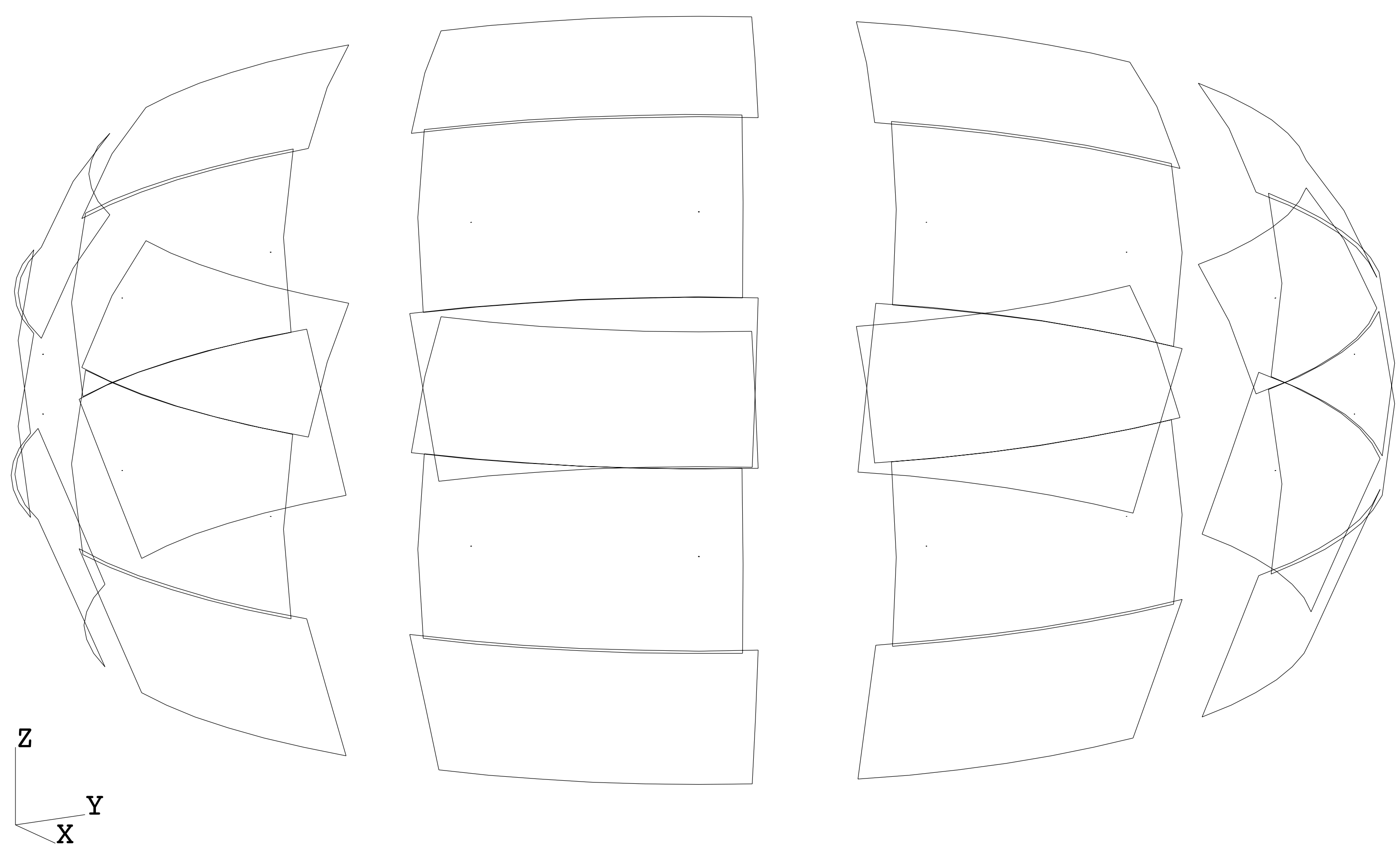
Why is nonrigid, multimode plasma response important?

Small modular coils needed in vessel for ITER/reactor





Small, Modular Internal Coils in ITER will possibly excite multiple plasma modes



3D finite element VALEN model of VAC02 coilset

Can lead to “nonrigid,” multimode plasma response

- Expt/theory indicate that small coils can couple to other stable or unstable modes (large sideband harmonics)

- Leads to nonrigid mode (=multimode) behavior

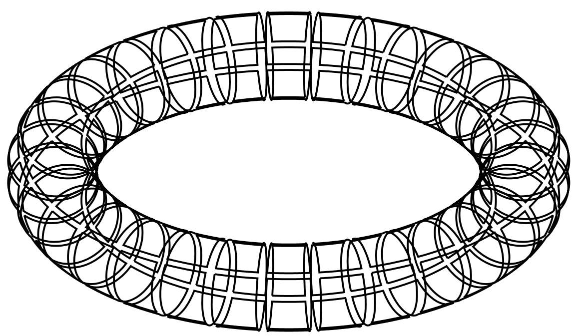
- Can lead to loss of feedback control and obscure RMP plasma response expts and impact plasma performance

- Can be hard to detect using “standard” tokamak magnetics

Examples of nonrigid, multimode kink plasma response

Nonrigid, multimode kink response: Ex-Trap T2R

Ex-Trap T2R, unstable multi-mode spectrum

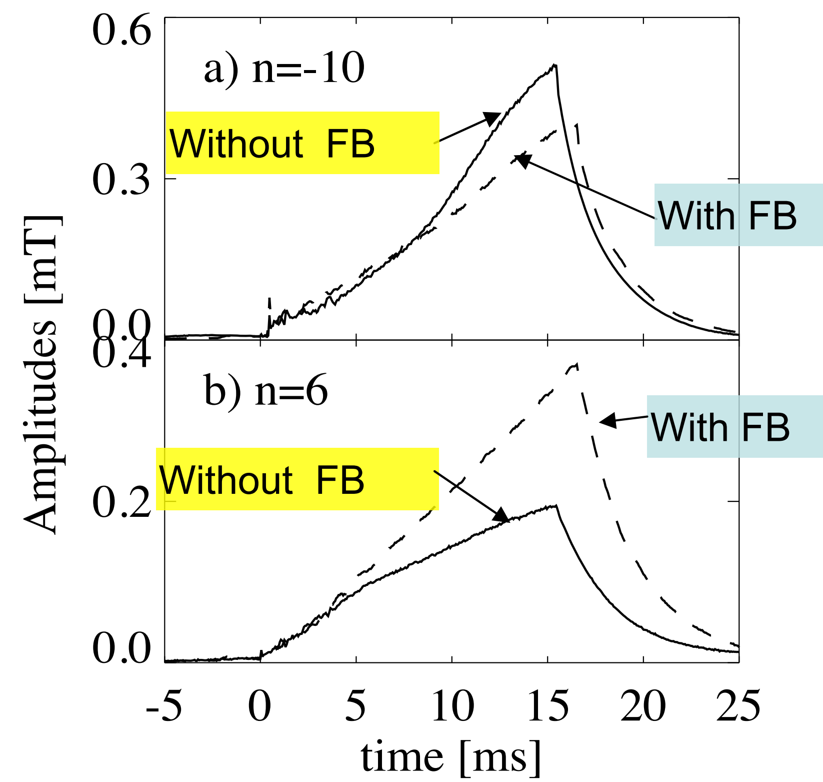


The toroidal side band effect with:

$M_c = 4$, N_c=16, $\Delta n_c = 16$

Compare the m=1,n = -10 mode and the coupled m=1, n =6 mode.

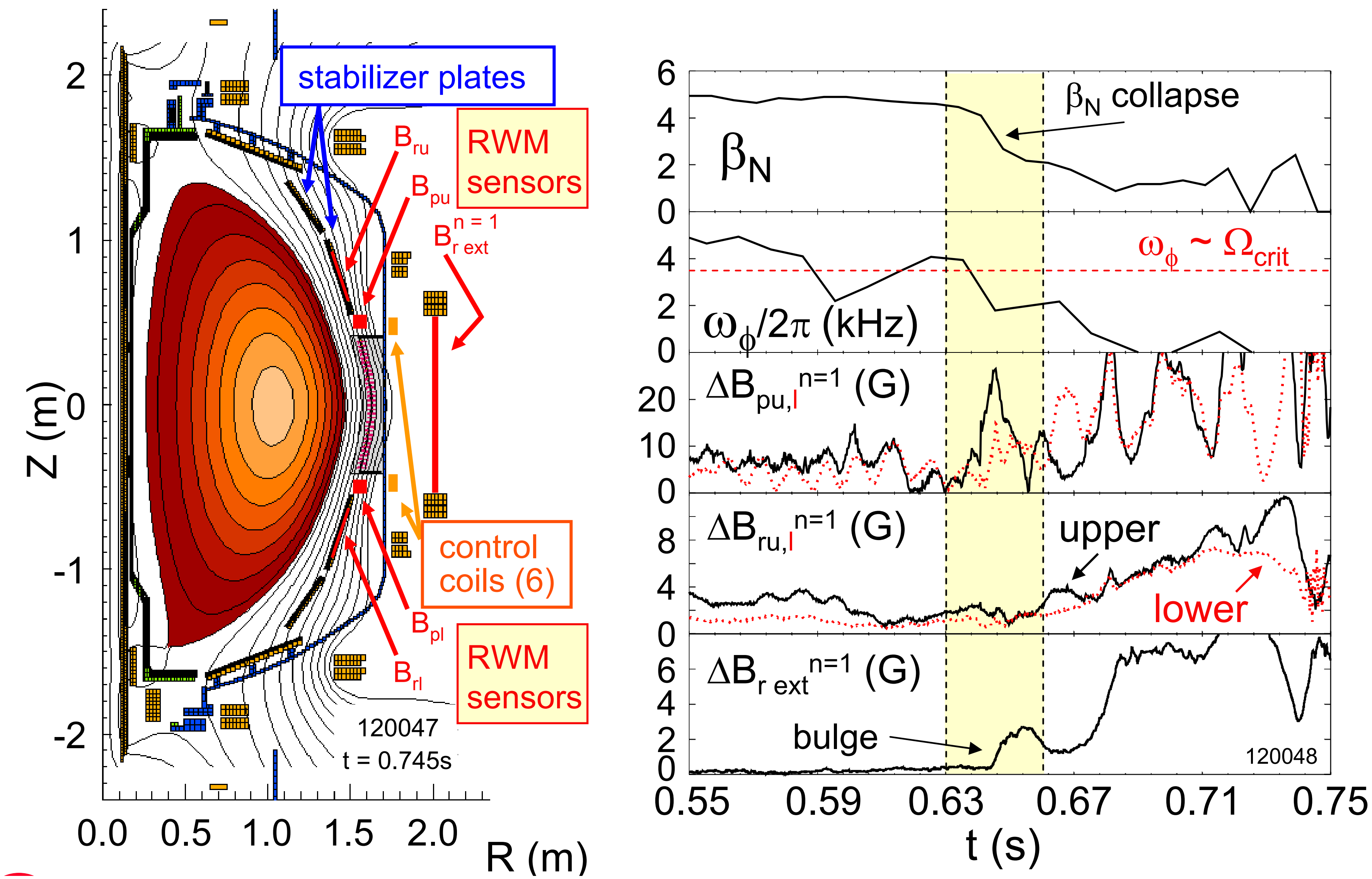
- The n=-10 mode is dominant, so the sideband effect of the n = -10 mode on the n = 6 mode dominates.
- The end result is a partial suppression of the n = -10 mode and faster growth of the n=6 mode.
- Both modes have the same amplitude with fb



Yadikin, et al., PPCF, 48, 1, (2006)
Brunsell, et al, NF, 24, 904, (2006)

Nonrigid, multimode kink response: NSTX

NSTX example, 1 unstable mode and possible stable spectrum excitation

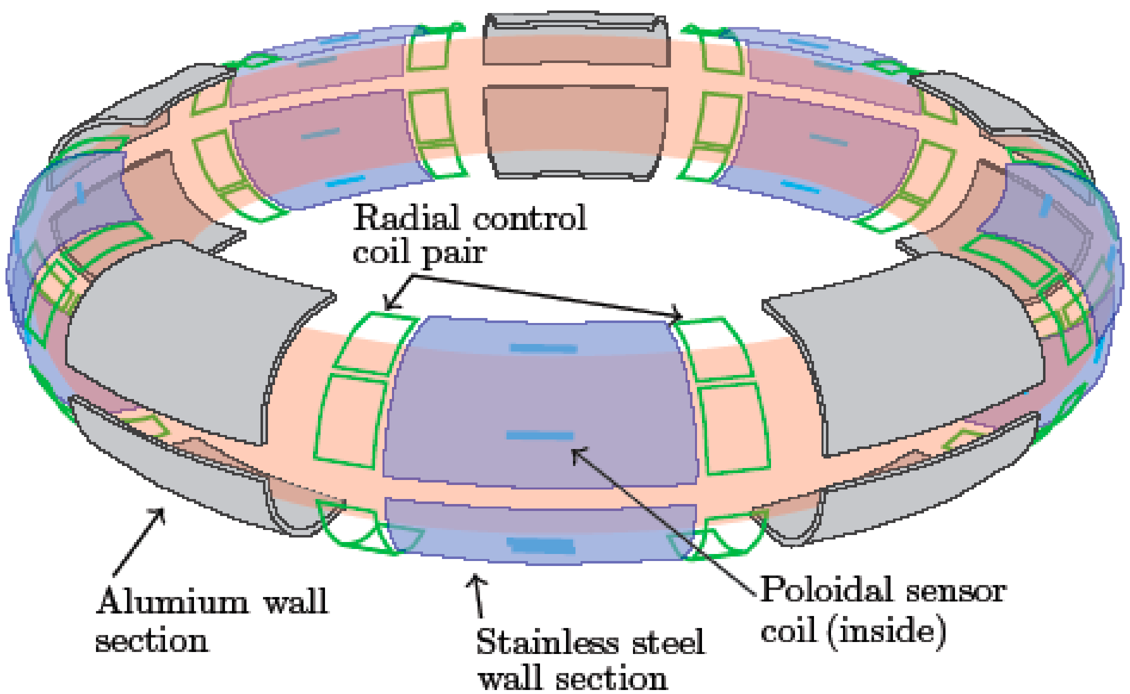


- Poloidal n = 1 RWM field decreases to near zero
  - Radial field increasing
- Subsequent growth of poloidal RWM field
  - *Asymmetric* above/below midplane
- Radial sensors show RWM bulging at midplane
  - midplane signal increases, upper/lower signals decrease
  - Theory: may be due to other stable ideal n = 1 modes becoming less stable

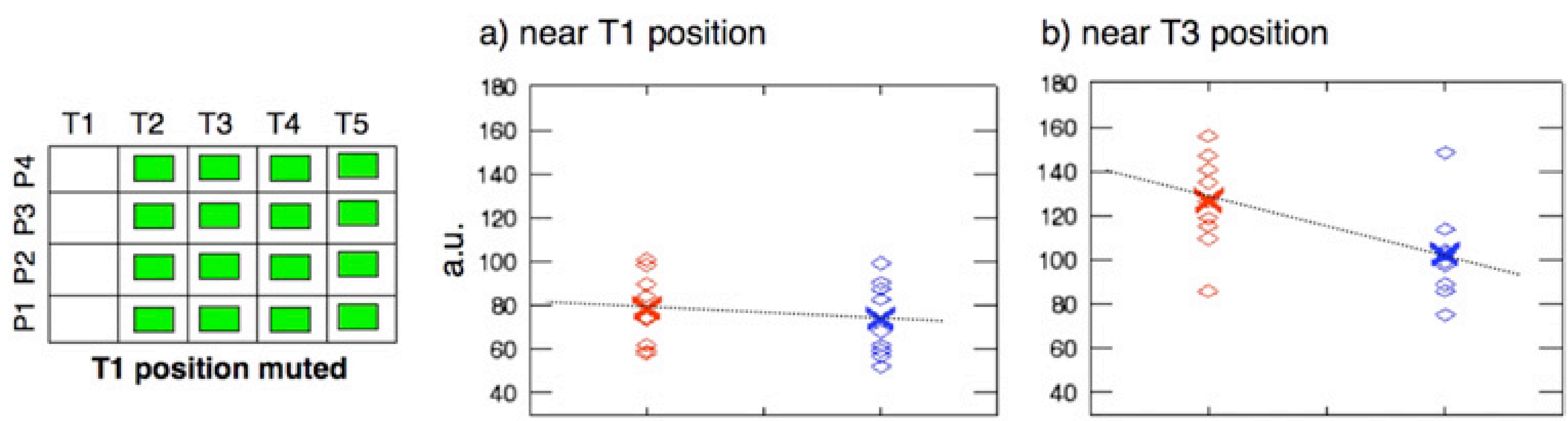
Future research will assess using combined sensors for optimization

Sabbagh, et al., PRL, 97 045004, (2006)

Nonrigid, multimode kink response: HBT-EP



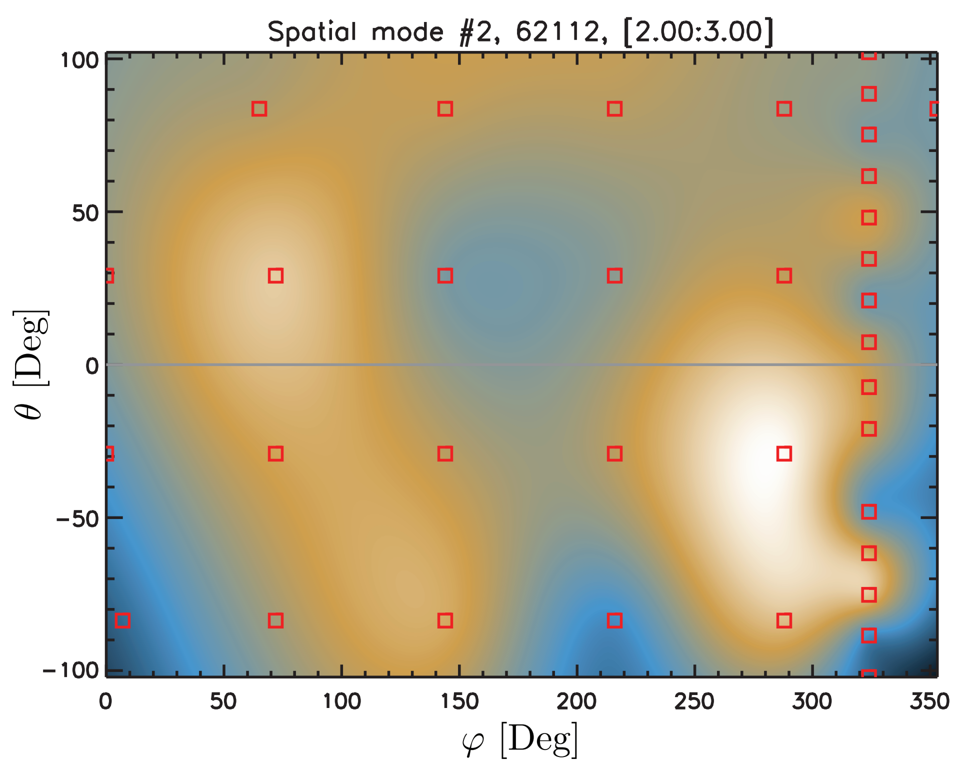
HBT-EP example: differing local plasma response of unstable mode while "muting" certain coil pairs

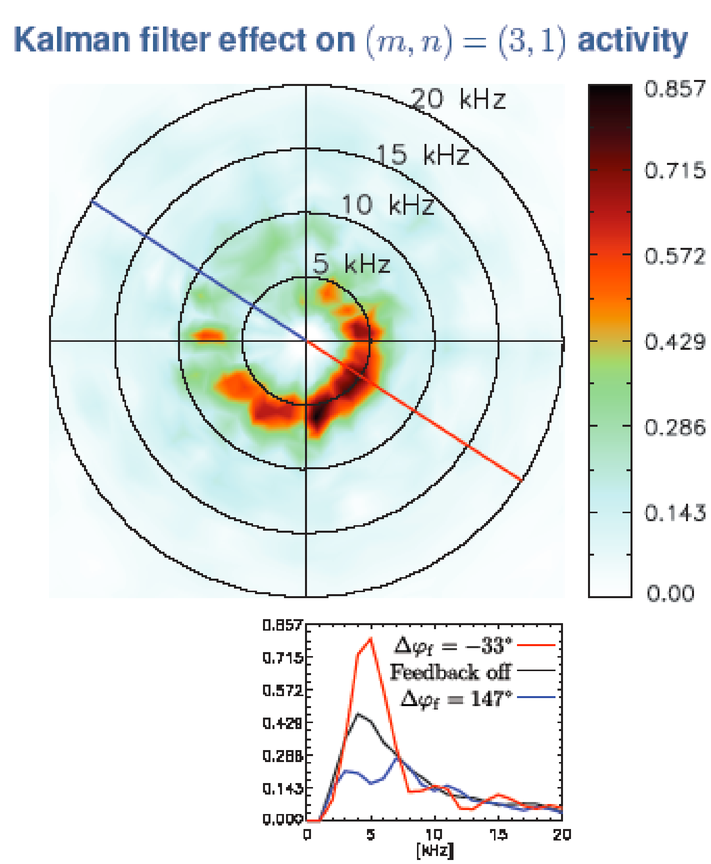


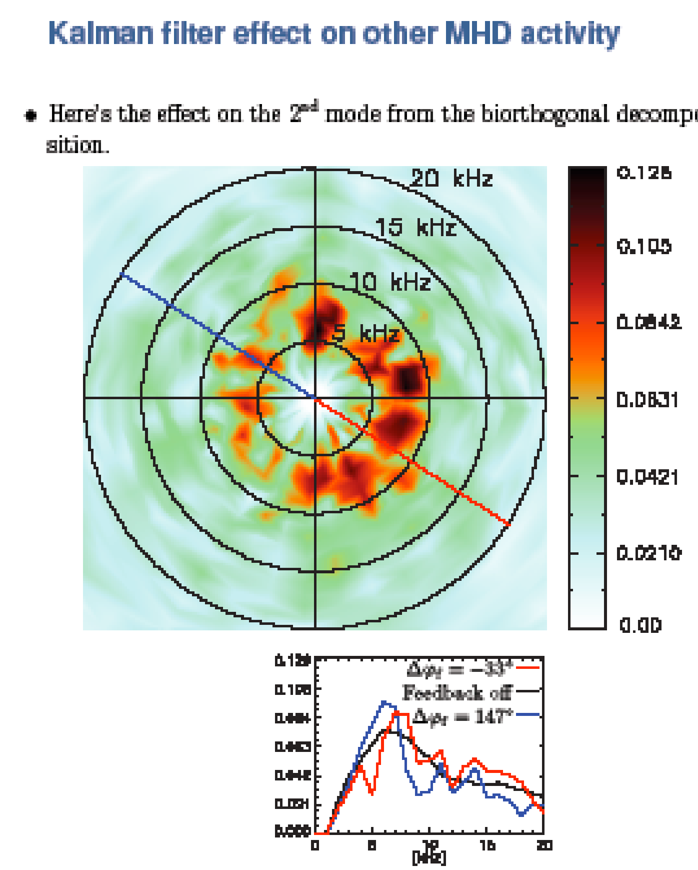
Pedersen, et al., NF, 47, 1293, (2007)

Nonrigid, multimode kink response: HBT-EP

HBT-EP example: Is the n=2 response stable or unstable?

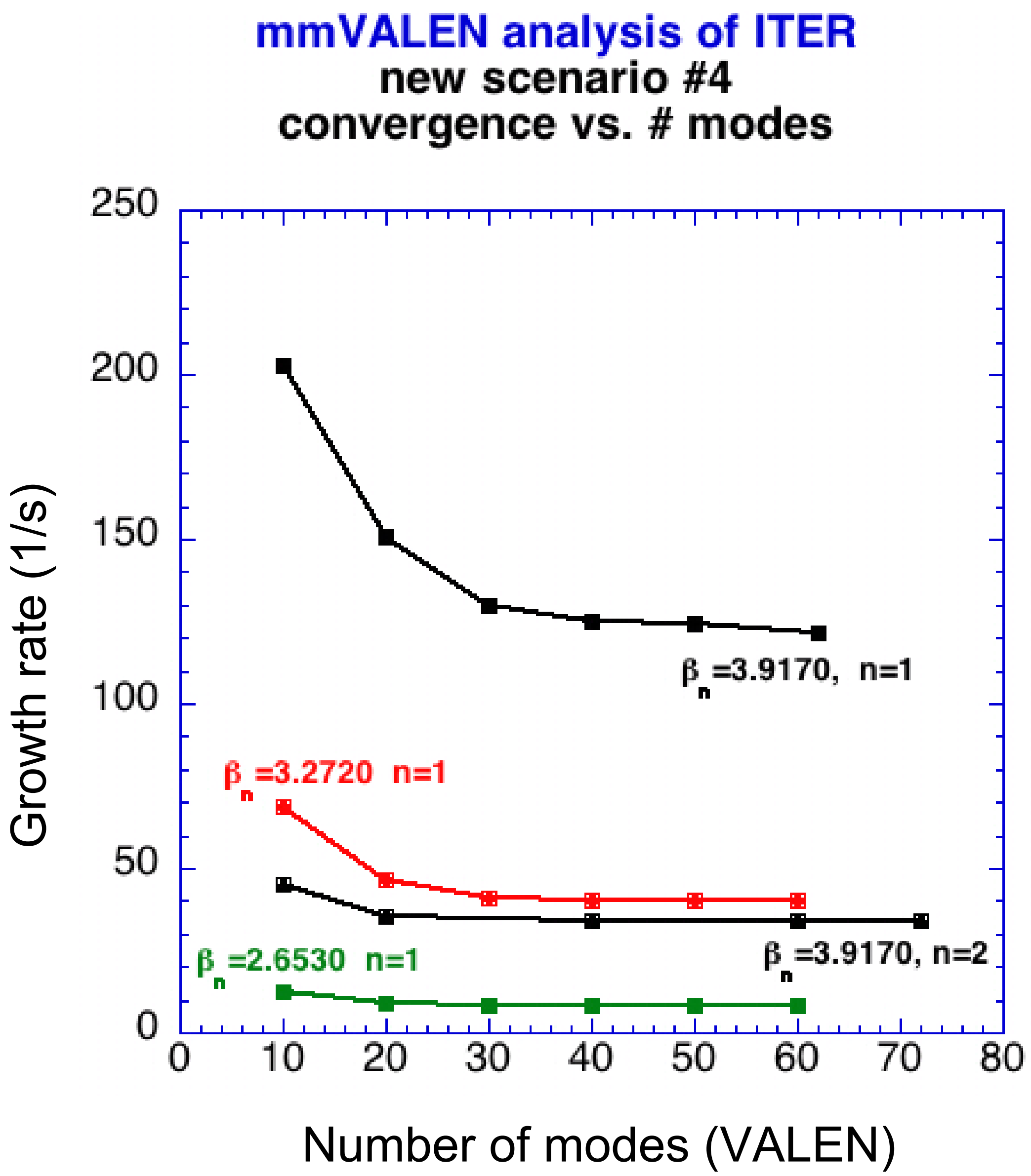




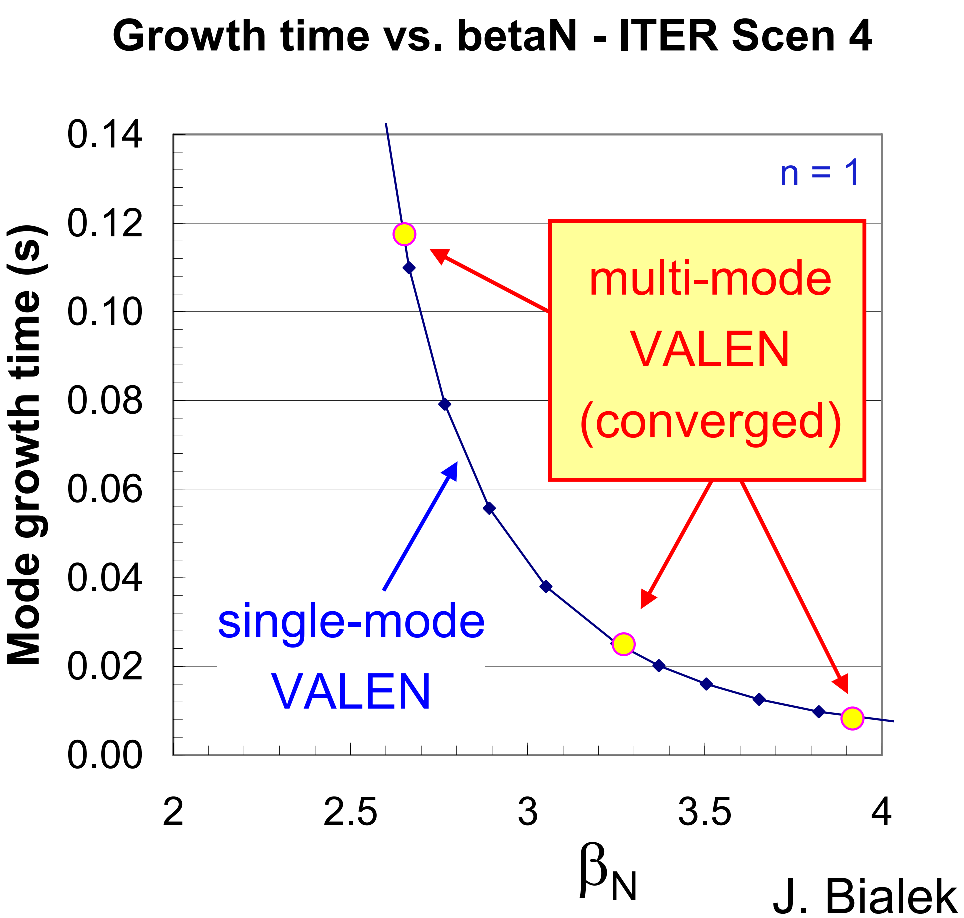


Hanson, et al., PoP, 16,056112, (2009)

n=1 and 2 predicated unstable at high pressure in ITER



- At highest β_N, n =1 and 2 are unstable



- DCON δW shows several modes with high response
  - Three n = 1 modes at high β_N
  - Two n = 2 modes at high β_N

J. Bialek, S. Sabbagh

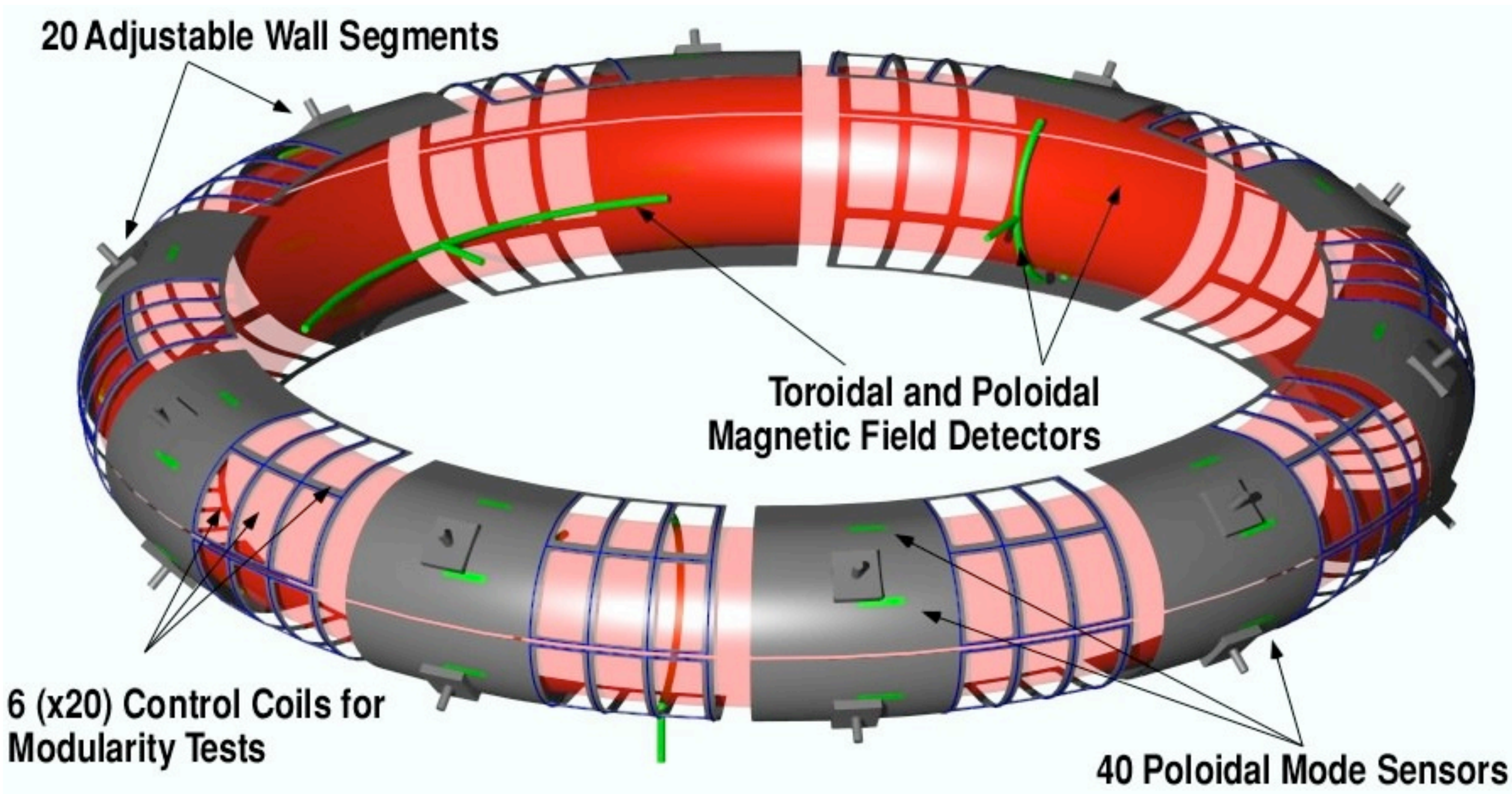
Why investigate these effects on HBT-EP?

Why investigate these issues on HBT-EP?

- Experimental measurements on HBT-EP are:

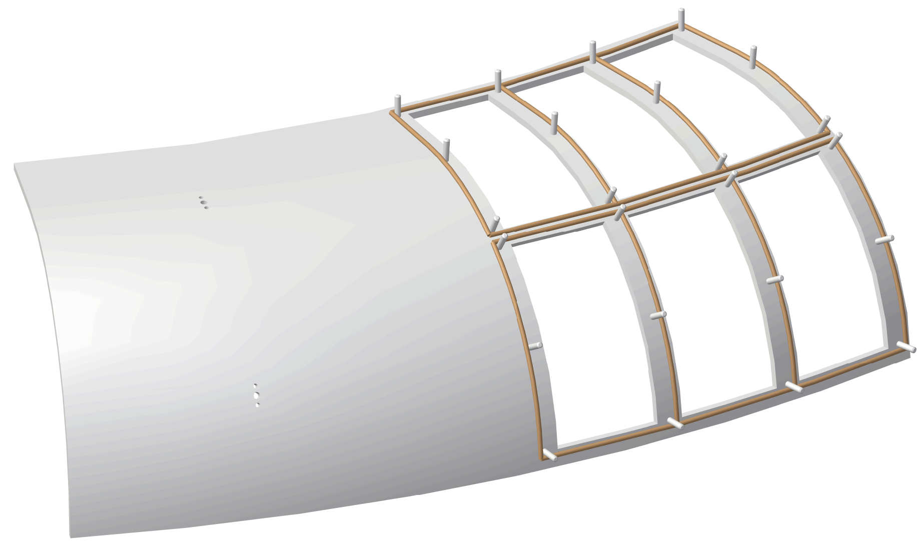
- Easy to implement with large sets of control and sensors coils and power supplies at low cost
- “Unlimited” runtime
- “Clean” high field side magnetic diagnosis of multiple modes possible
- Cylindrical/slab theory better approximation than in large devices for basic theory validation
- “Simpler” fluid theory applicable
- VALEN multimode plasma response benchmark

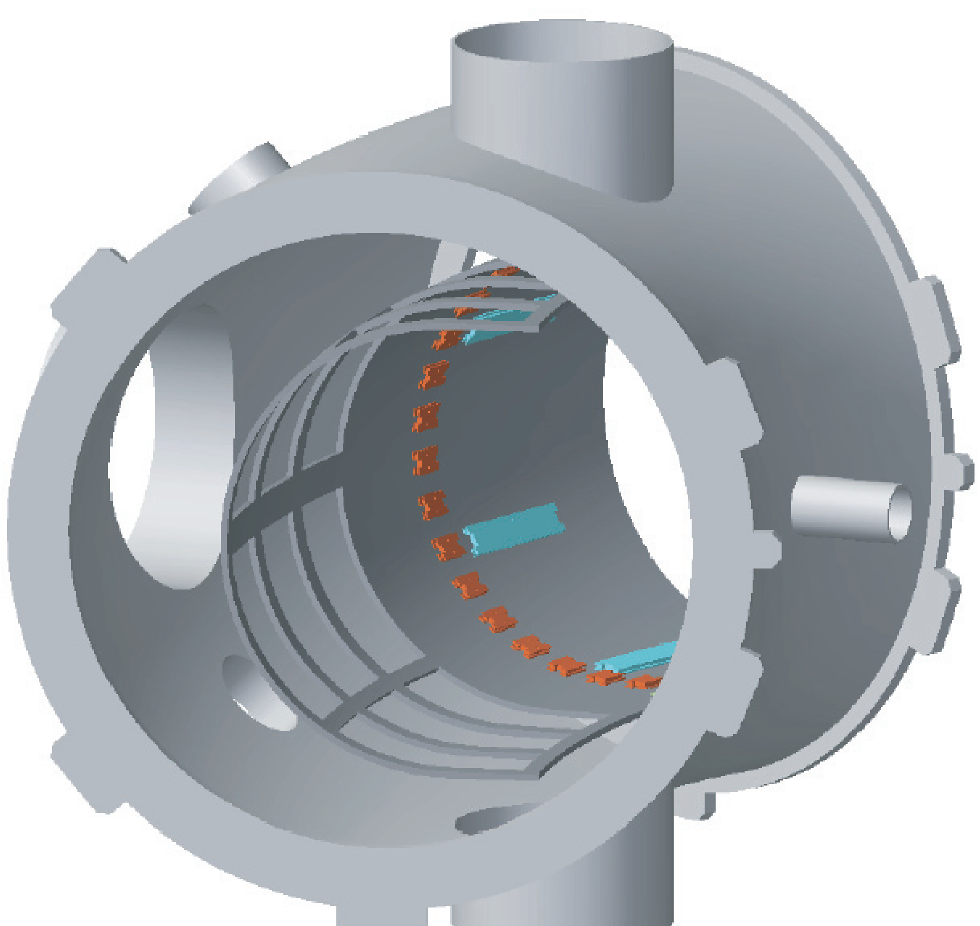
Investigating these issues on HBT-EP

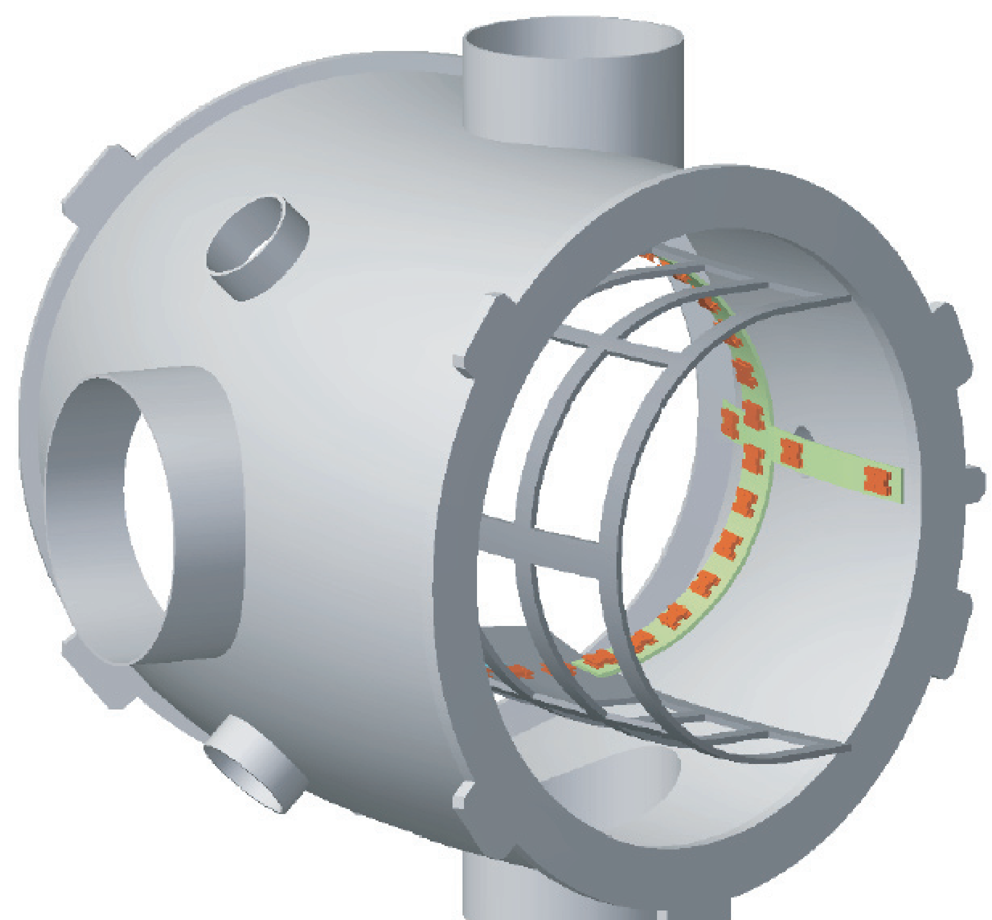


New wall, control and sensor coil arrays

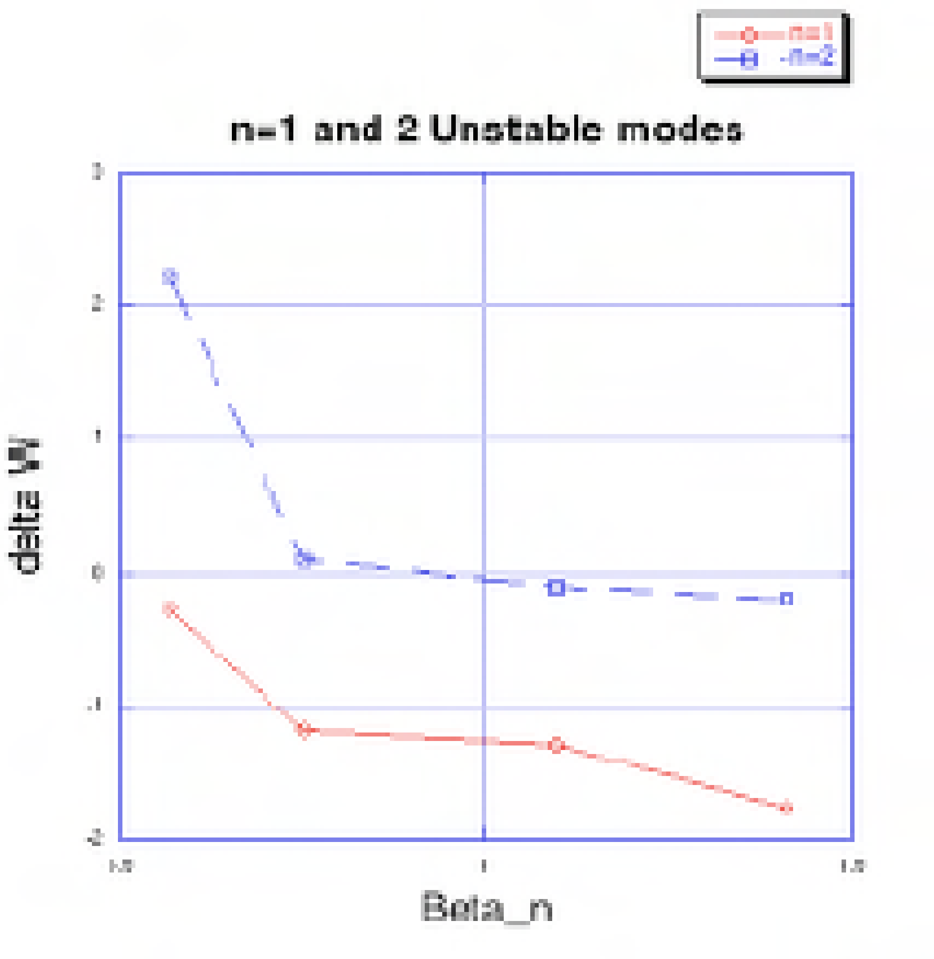
HBT-EP new wall, control and sensor coils arrays



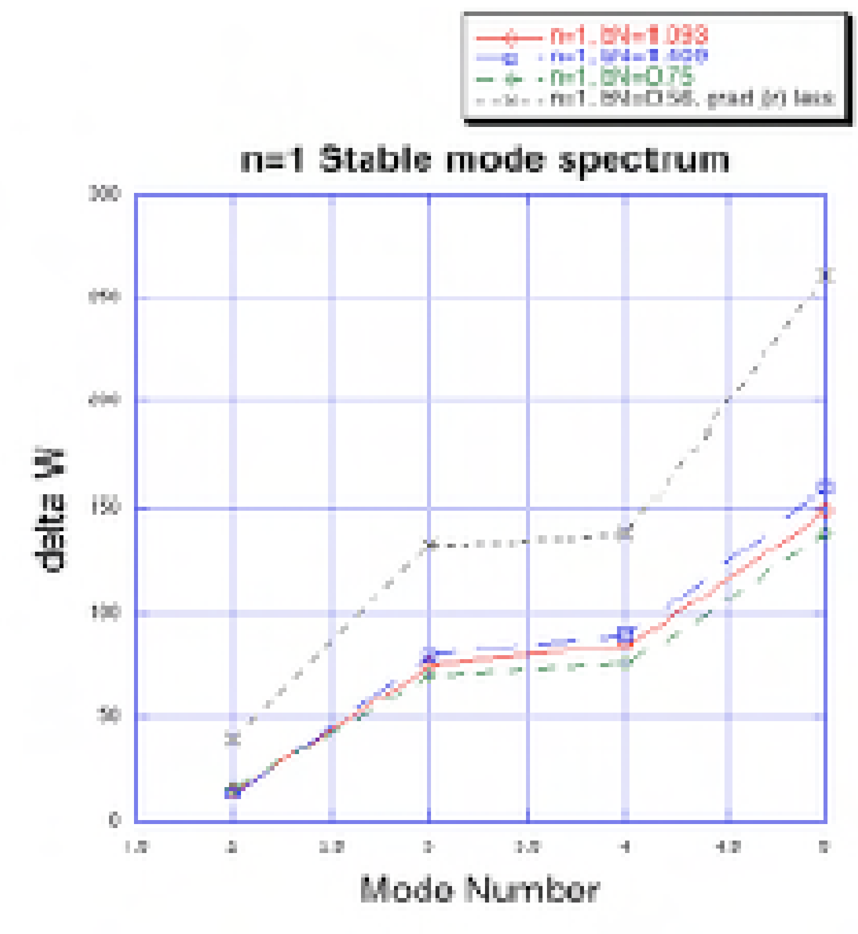




Multimode VALEN has been benchmarked and is up and running



Unstable n=1,2 at modest BetaN

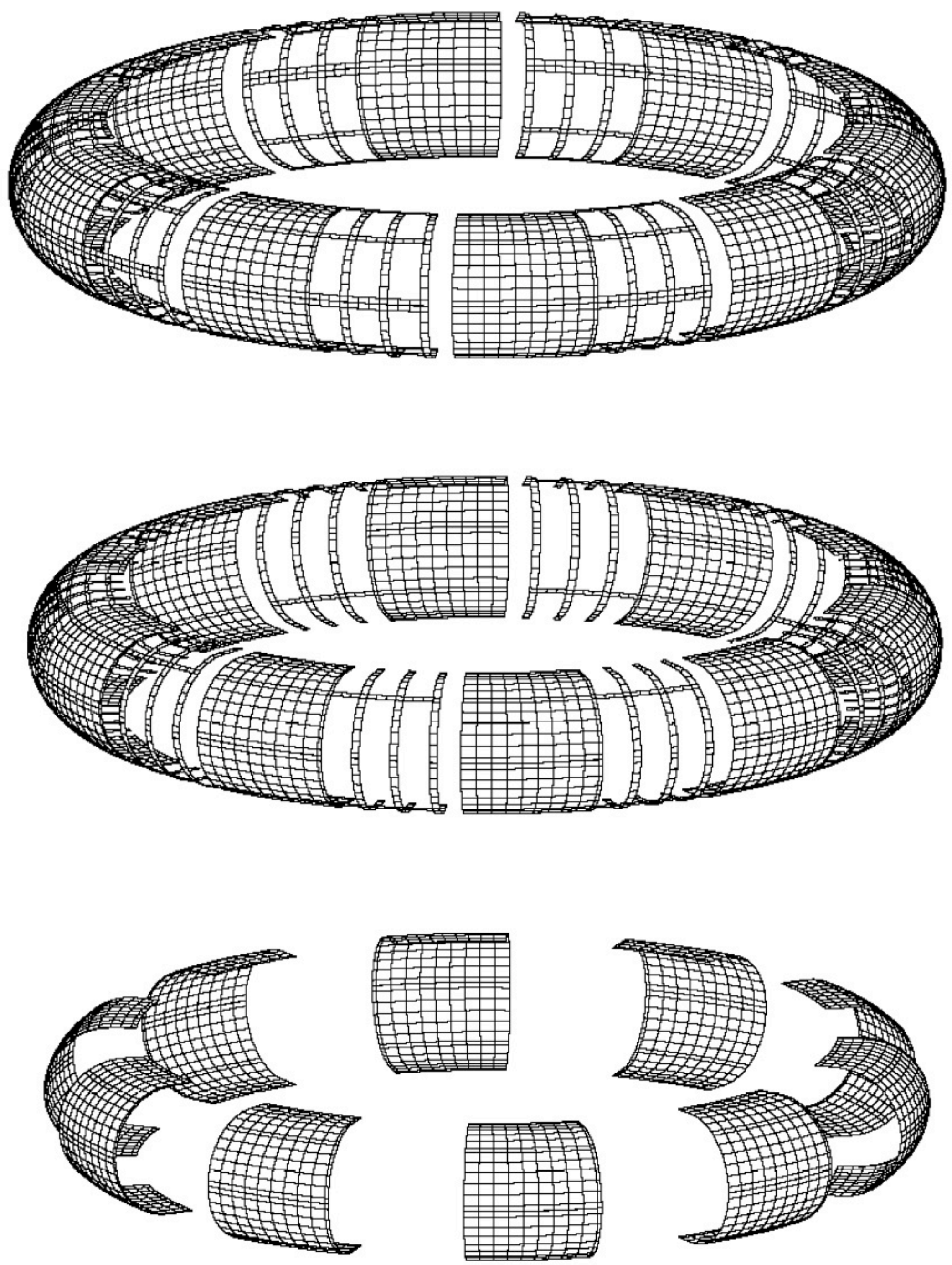


Stable n=1 mode spectrum

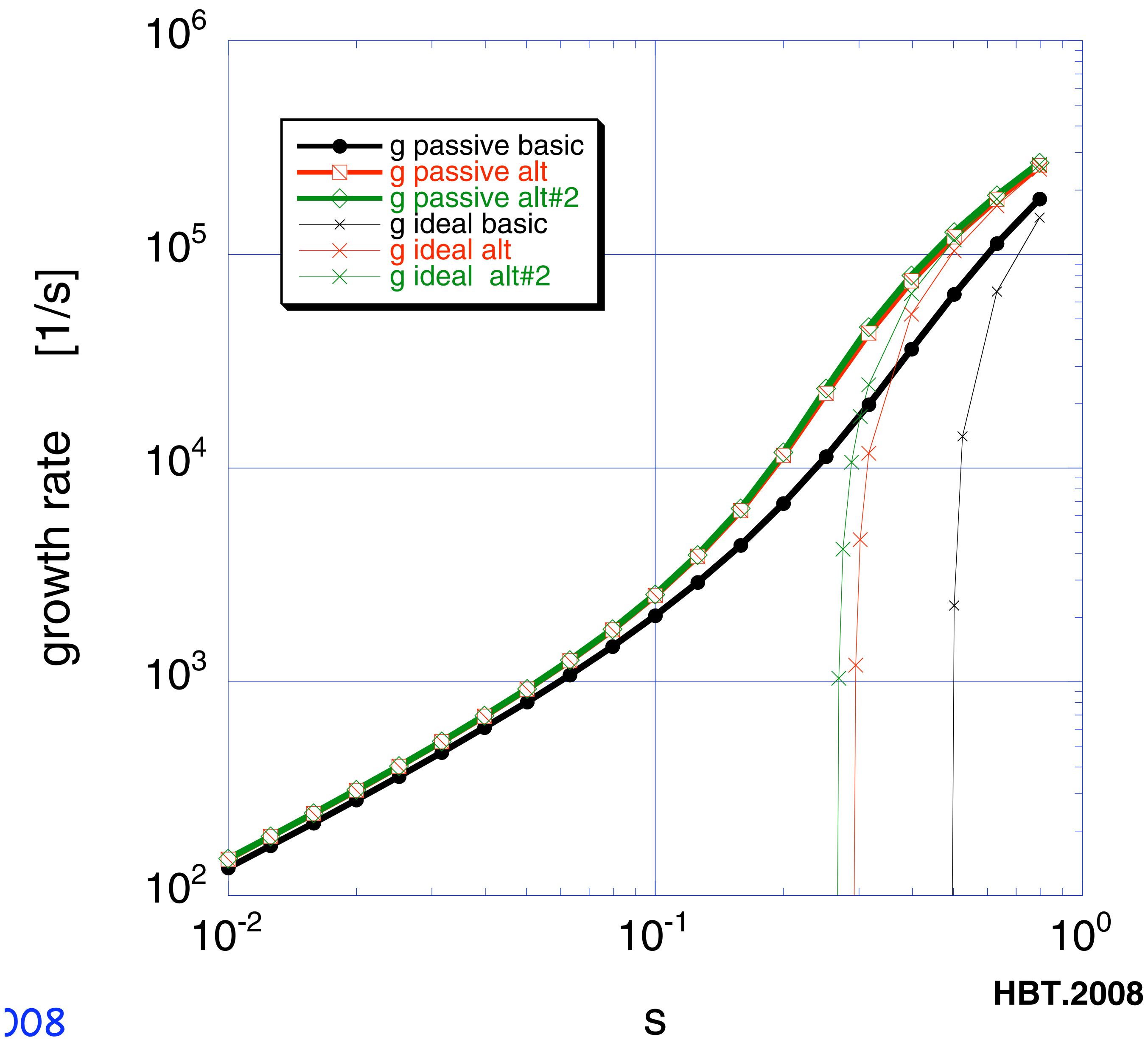
Feedback calculations underway...

J. Bialek,
Wednesday morning

New ideal wall limit increases window of RWM instability



Ideal limit increased by factor ~2 compared to old wall



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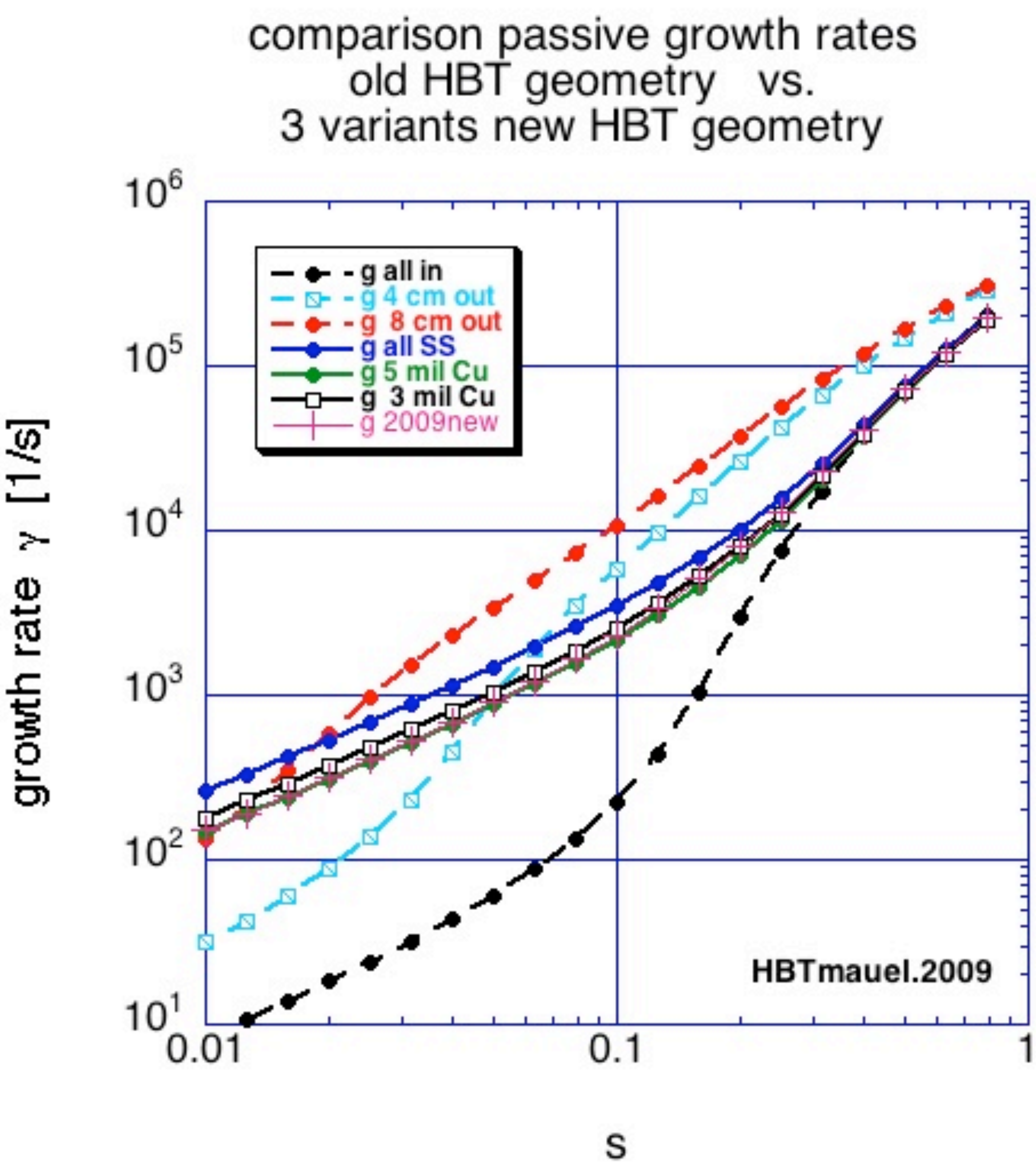
Designing the wall diffusion time



- Technical/manufacturing constraint: must use 3/16 inch S. Steel

- Electroplate 5 mils of Cu on the continuous portion of the shell to slow down the mode growth by ~2

- Electroplate whole shell with 1/2 mil of Cr to "protect" Cu

New wall construction: Spinning Stainless Steel “Pans”

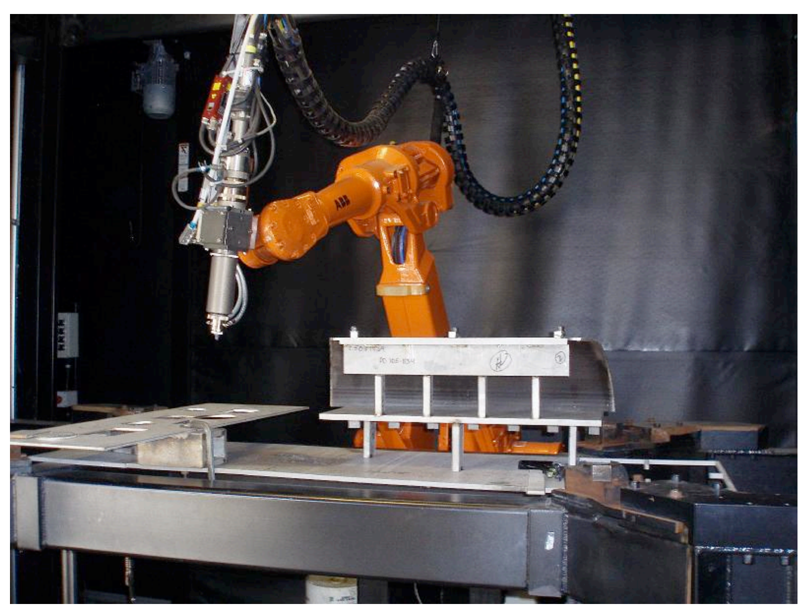



- Spinning work hardens and embeds large residual stresses in the pans

- Solution: anneal to 1850 F

Annealed pan "edges" ready for machining

- Bead blasted pan "edge" laser cut into shell segments with window panes

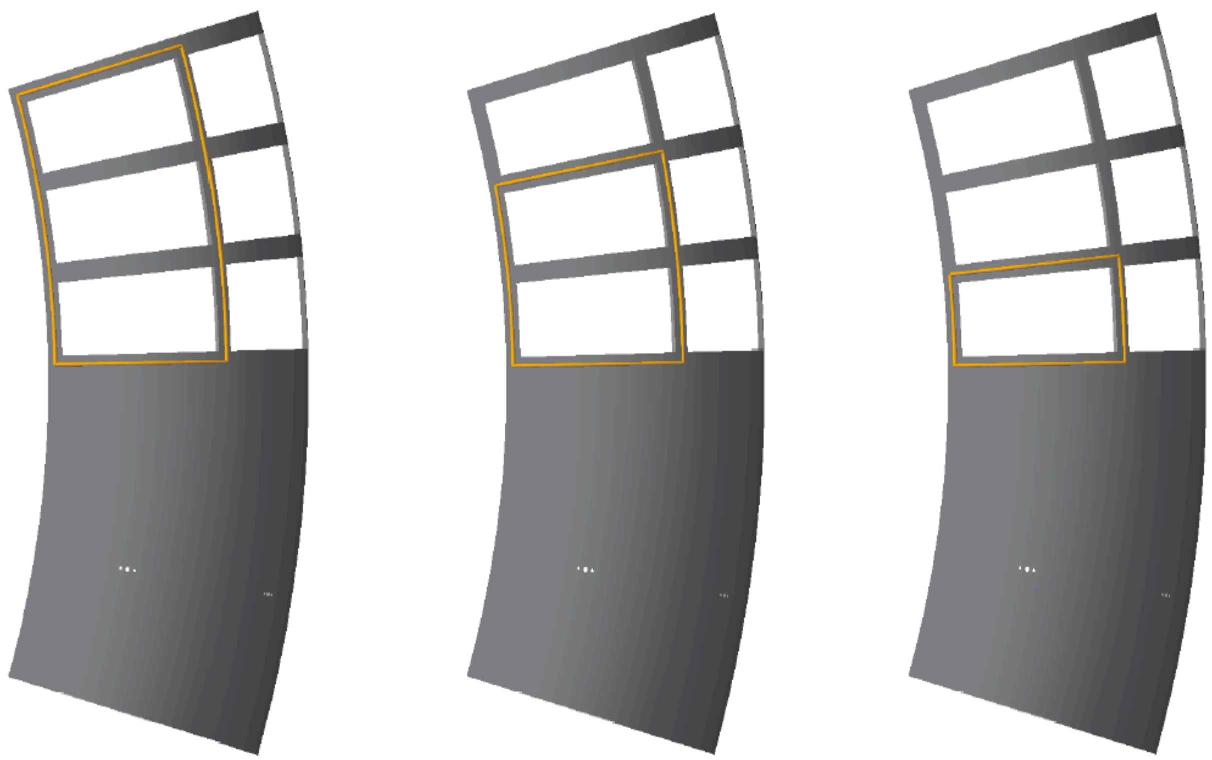


The (almost) finished product...

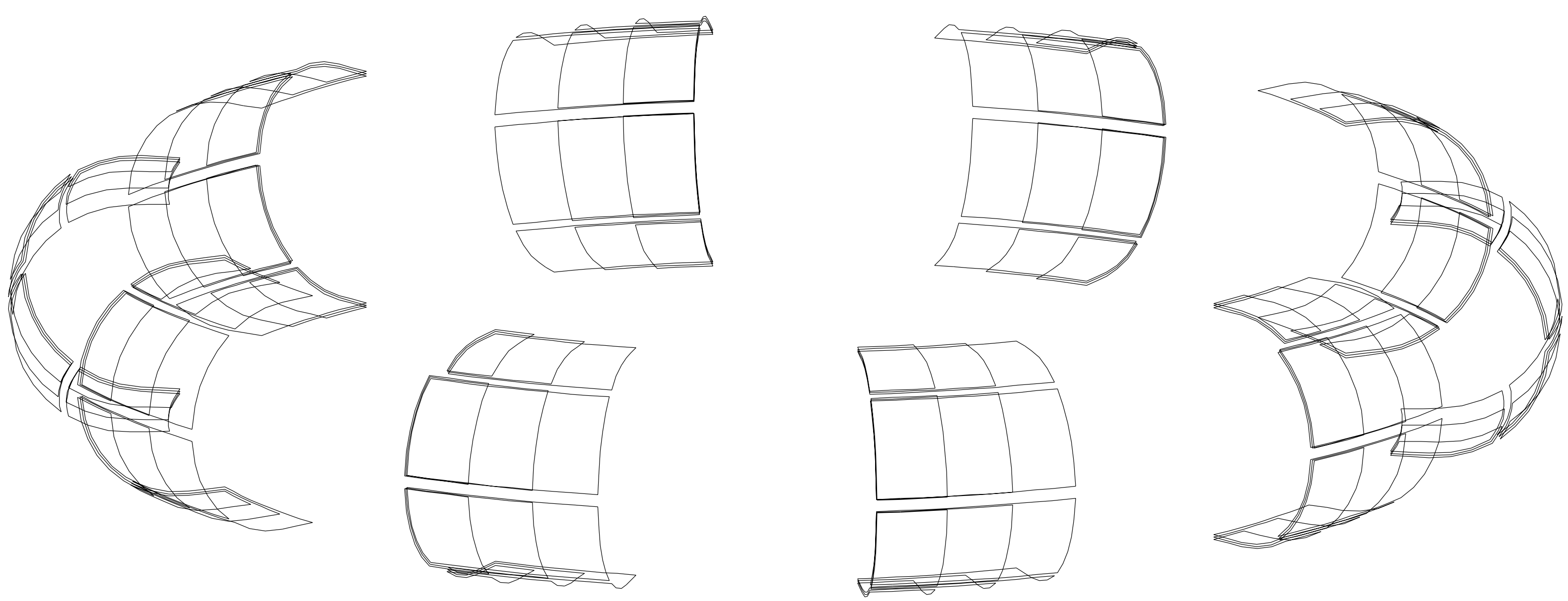
• Initial sample measurements have the shell conformal to the design surface to < 1mm

Next steps: Electropolishing, electroplating, and control coil winding and sensor installation

New control coil design/construction

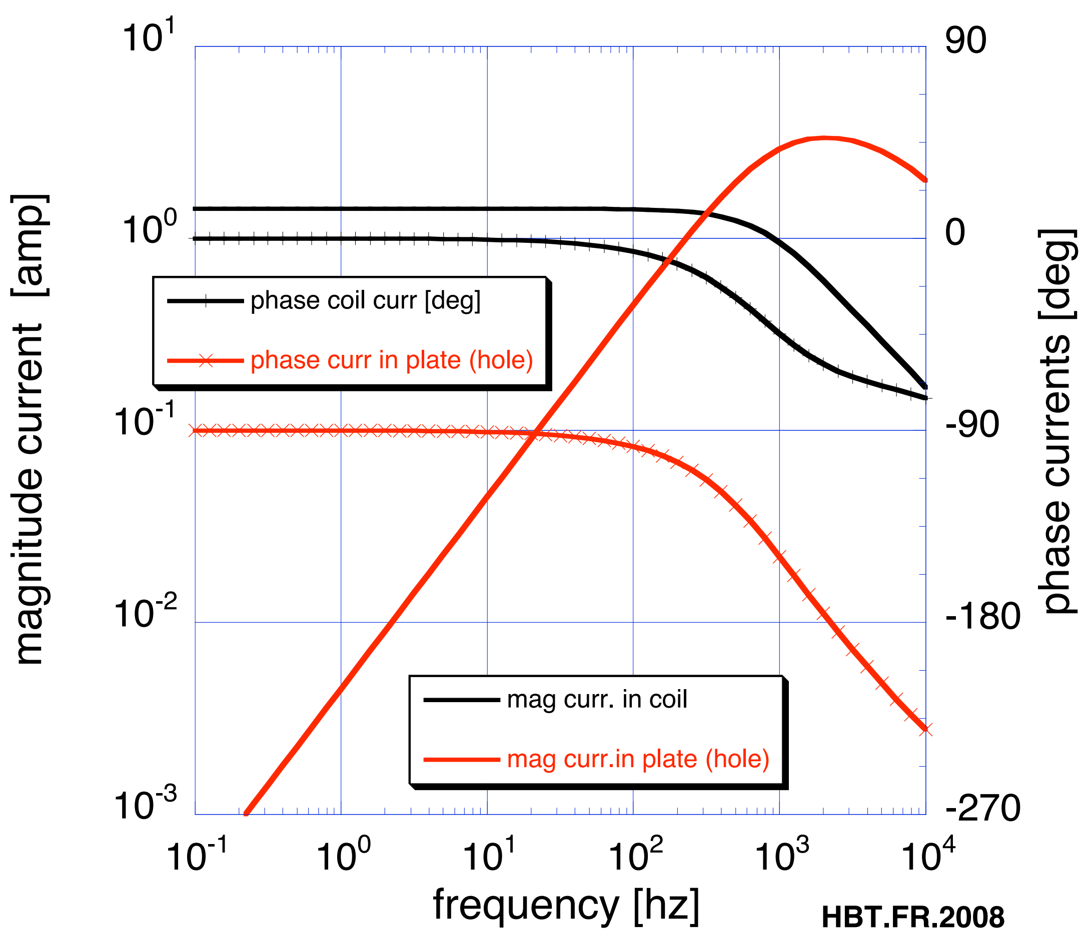


- Total of 120 new control coils
  - 3 “flavors” with 5, 10, 15 degree toroidal angular extent

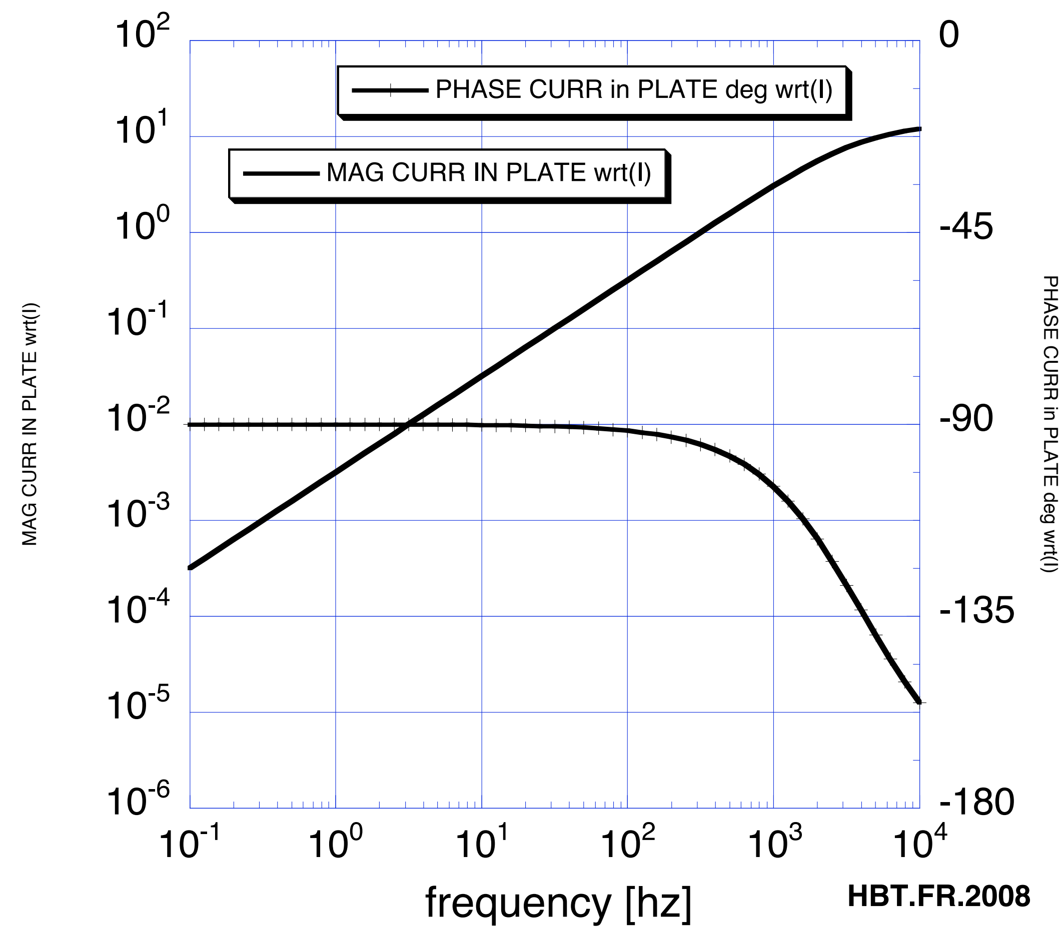


Control coil-wall eddy current coupling

results wrt voltage

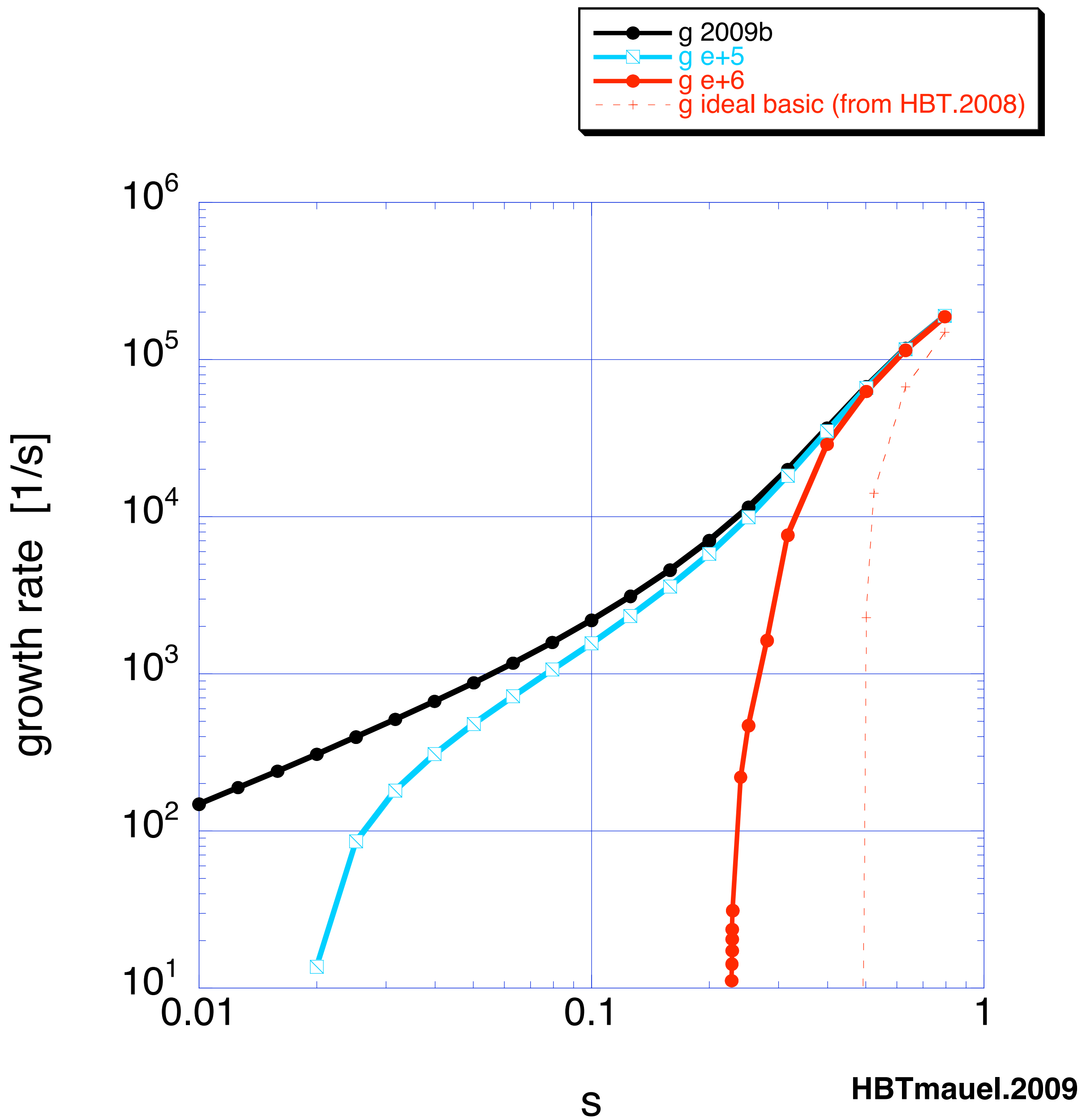


results wrt coil current

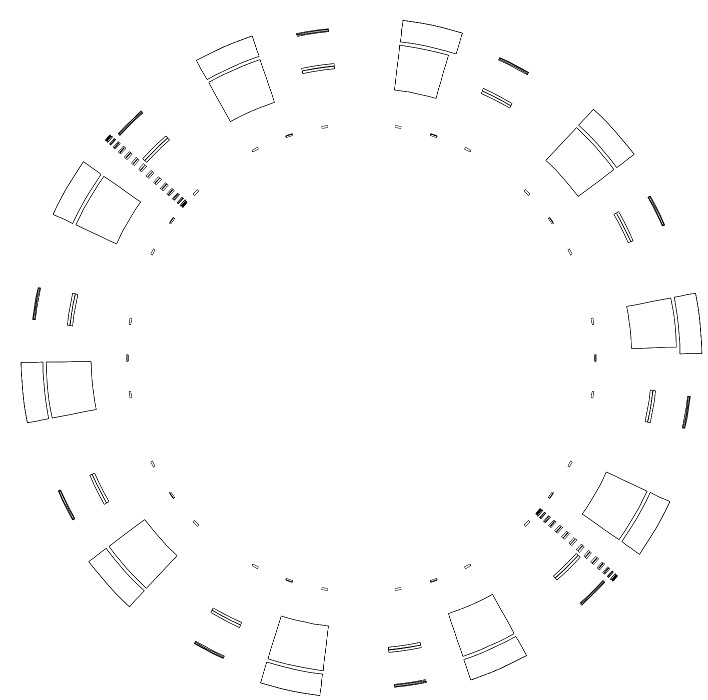


- Window pane stainless steel induced eddy currents are a ~10 to 20% effect

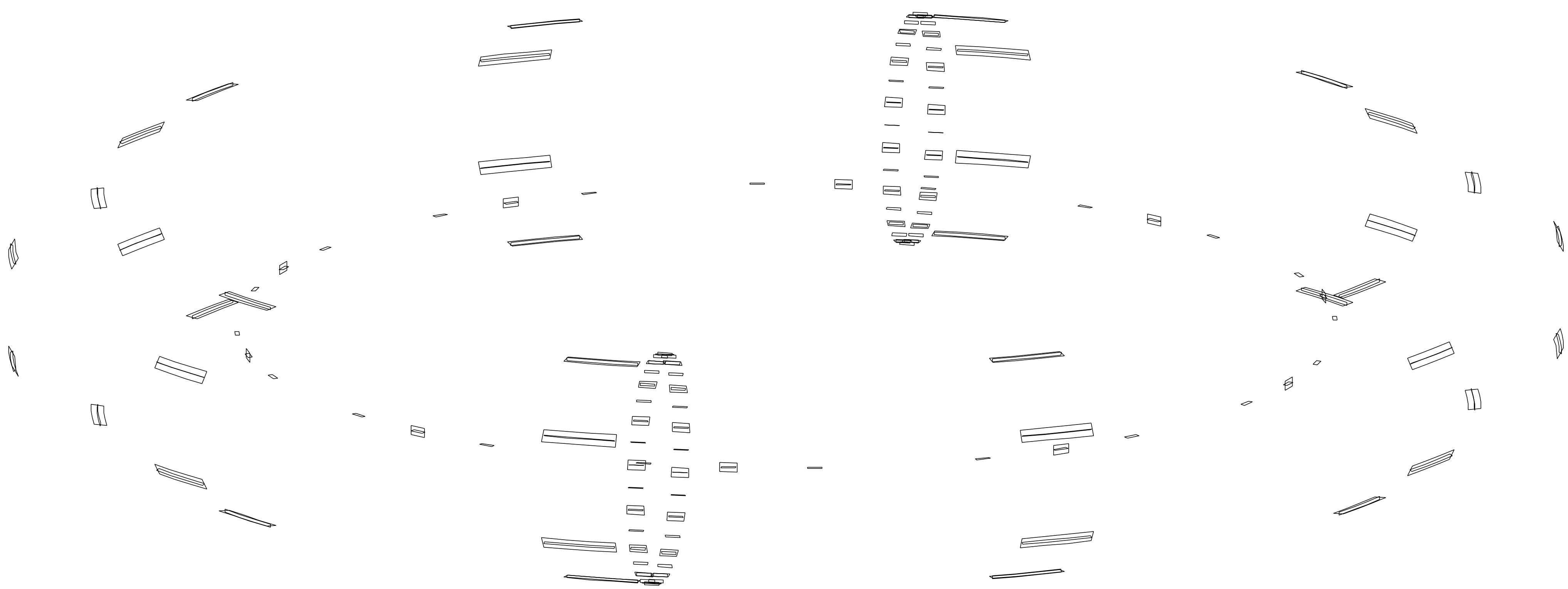
Feedback Performance: 10 degree coils



- Single mode VALEN calculation
- Stabilization up to 1/2 the ideal limit
- Multimode feedback VALEN calculations started



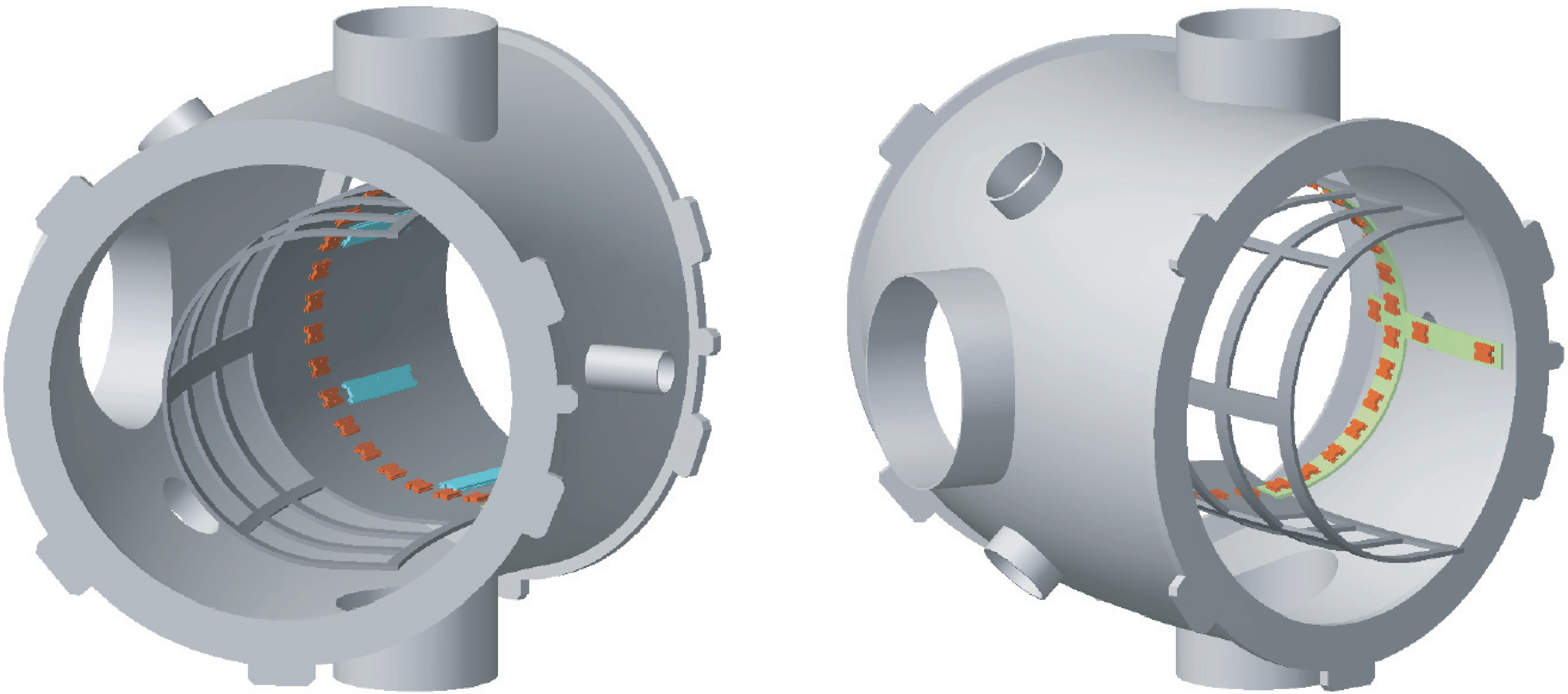
New magnetic sensor arrays to measure multimode plasma response



216 new magnetic pickup sensors, n~14, m~15

Along with new preamps and digitizers

New magnetic sensor arrays in vessel



Calibration method/technique

- The signal in a sensor from coil i is

$$S_i = \mathbf{B}_i(x, y, z) \cdot \hat{\mathbf{n}}(\xi_1, \xi_2)$$

At the k^{th} iteration, our guess of the sensor placement is $\mathbf{x}^k = (x^k, y^k, z^k, \xi_1^k, \xi_2^k)$ with error $\delta\mathbf{x}^k = \mathbf{x}^{true} - \mathbf{x}^k$.

- Expanding to first order about our current guess $\mathbf{x}^k$, we have $S_i = S_i^k + \delta S_i^k$ where

$$S_i^k = \mathbf{B}_i(x^k, y^k, z^k) \cdot \hat{\mathbf{n}}(\xi_1^k, \xi_2^k)$$

is the "zeroth order" term, and

$$\delta S_i^k = \left.\frac{\partial S_i}{\partial x}\right|_{\mathbf{x}^k} \delta x^k + \left.\frac{\partial S_i}{\partial y}\right|_{\mathbf{x}^k} \delta y^k + \left.\frac{\partial S_i}{\partial z}\right|_{\mathbf{x}^k} \delta z^k + \left.\frac{\partial S_i}{\partial \xi_1}\right|_{\mathbf{x}^k} \delta \xi_1^k + \left.\frac{\partial S_i}{\partial \xi_2}\right|_{\mathbf{x}^k} \delta \xi_2^k$$

is the "first order" term.

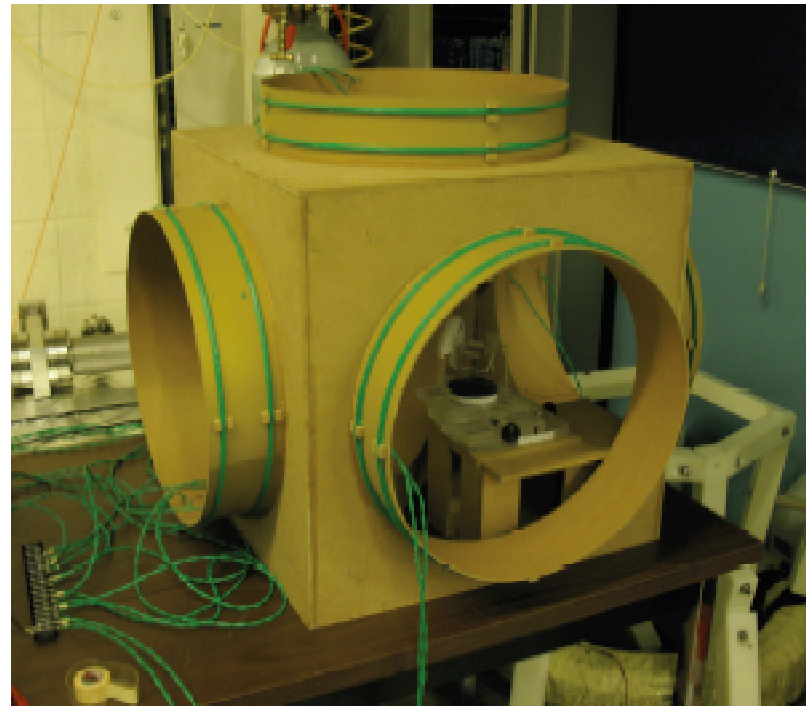
- If we have N coils, we get the matrix equation $(J^k) * \delta\mathbf{x}^k = S_i - S_i^k$ where J^k is the $N \times 5$ Jacobian matrix evaluated at $\mathbf{x}^k$. This equation is solved in a least-squares sense.

- Defining $\mathbf{x}^{k+1} = \mathbf{x}^k + \delta\mathbf{x}^k$, we have our new estimate. Assuming $\mathbf{x}^k$ is "close enough" to $\mathbf{x}^{true}$, $\mathbf{x}^{k+1}$ will be a better guess, and the same process is applied to linearize about $\mathbf{x}^{k+1}$ so that the process becomes iterative and the sequence of estimates $\{\mathbf{x}^k\}$ will converge to $\mathbf{x}^{true}$.

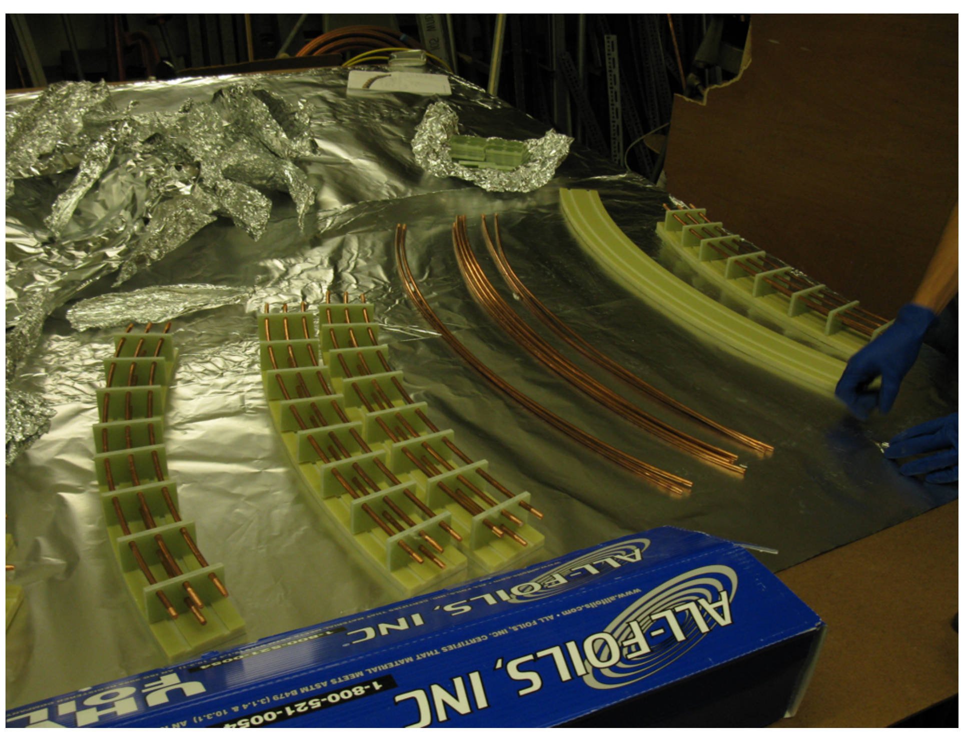
- Assumptions: Source coil location, NA and amplifer gains perfectly known. No eddy currents. No noise.

Sensor construction and calibration

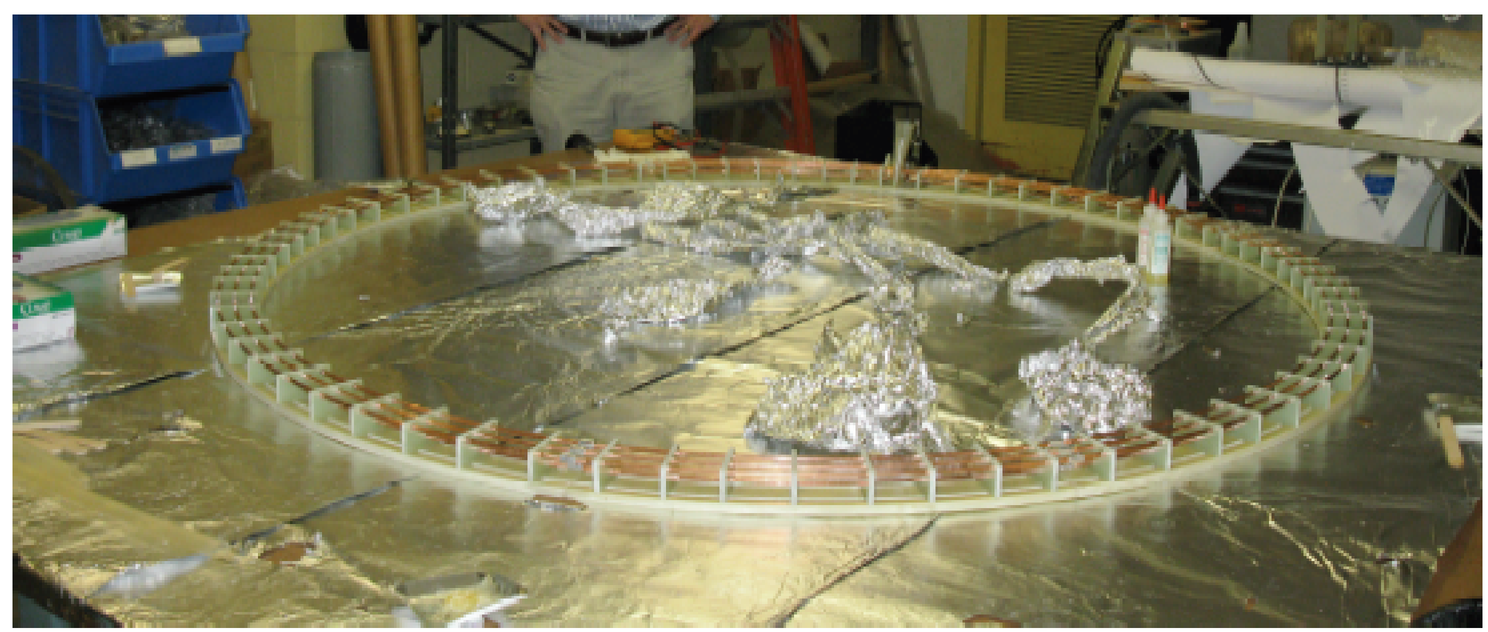
Bench tests



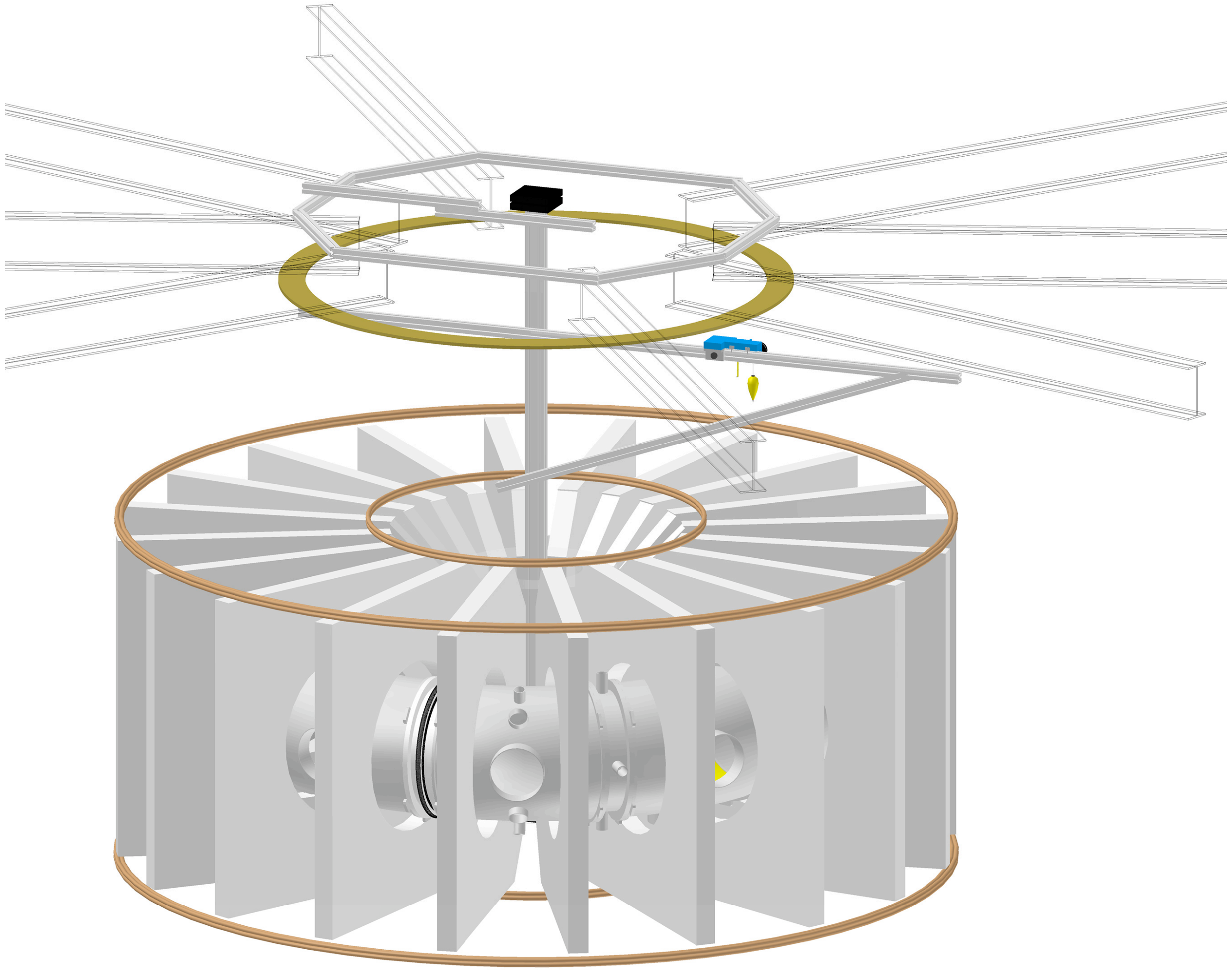
Typical sensors

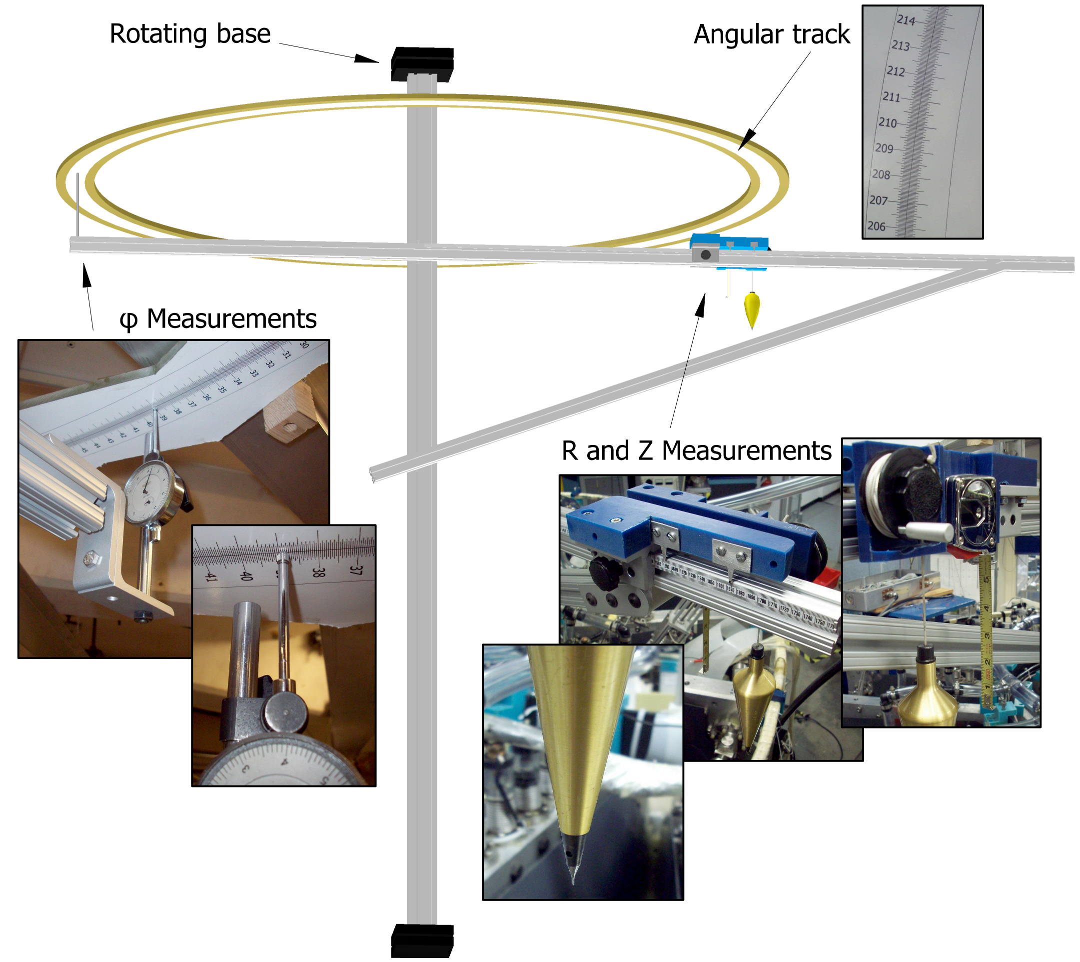


"Copper" plasma in-situ calibration



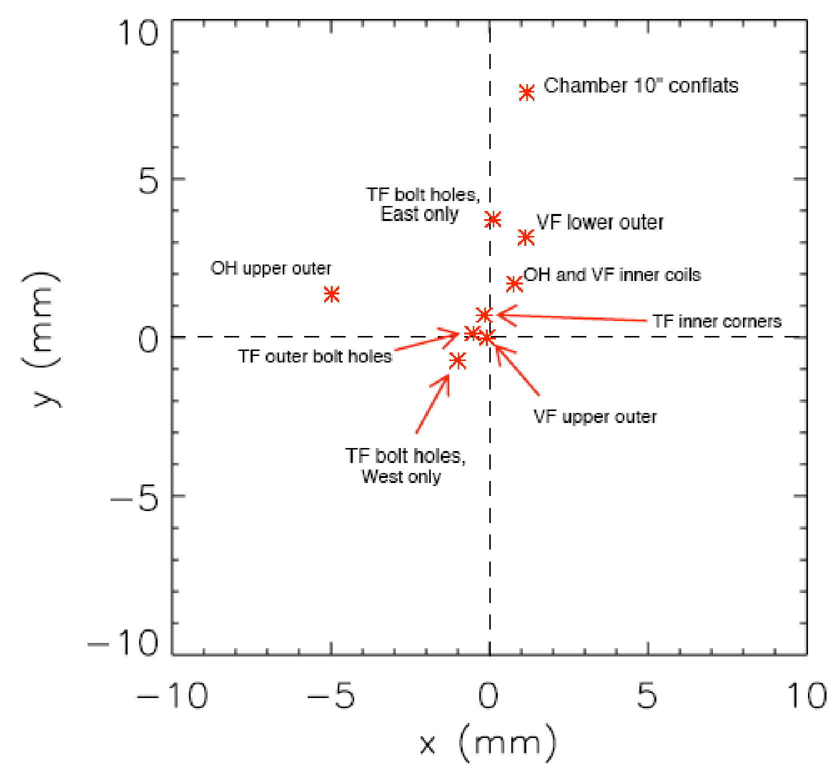
System installation and alignment





Accuracy: R~0.25mm,
Angle~1/80 degee, Z~1/64in

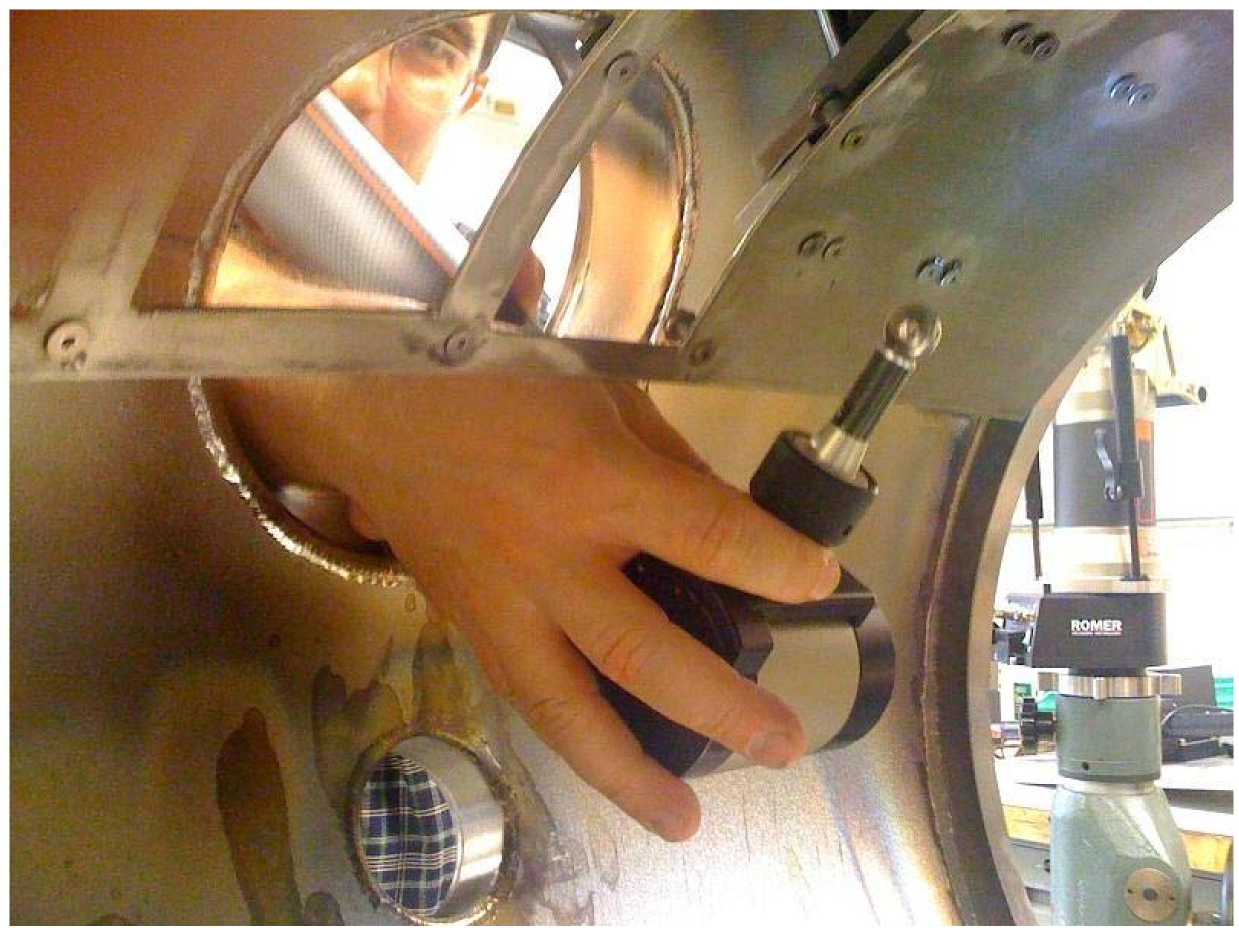
Calculated error fields due
to coil misalignments:
VF ~0.1G, TF ~10G



System installation and alignment

3D coordinate measuring arm for final installation measurements of shell position. Available via collaboration with PPPL.

Image source:
http://us.romer.com/infinite-2-0



Thanks to Phil Efthimion and Steve Raftopoulos

Summary and conclusions

• HBT-EP is in the process of successfully installing a new wall, control, and sensor system for mutlimode plasma response studies

• This system will allow new and novel experiments on multimode plasma response during kink feedback, magnetic spectroscopy, and edge ergodization experiments using our new control coils to drive plasma response and our new extensive array of magnetic sensors to quantify it.

Special thanks to

- Jeff Levesque
- Diasuke Shiraki
- Bryan DeBono
- Nickolaus Rath